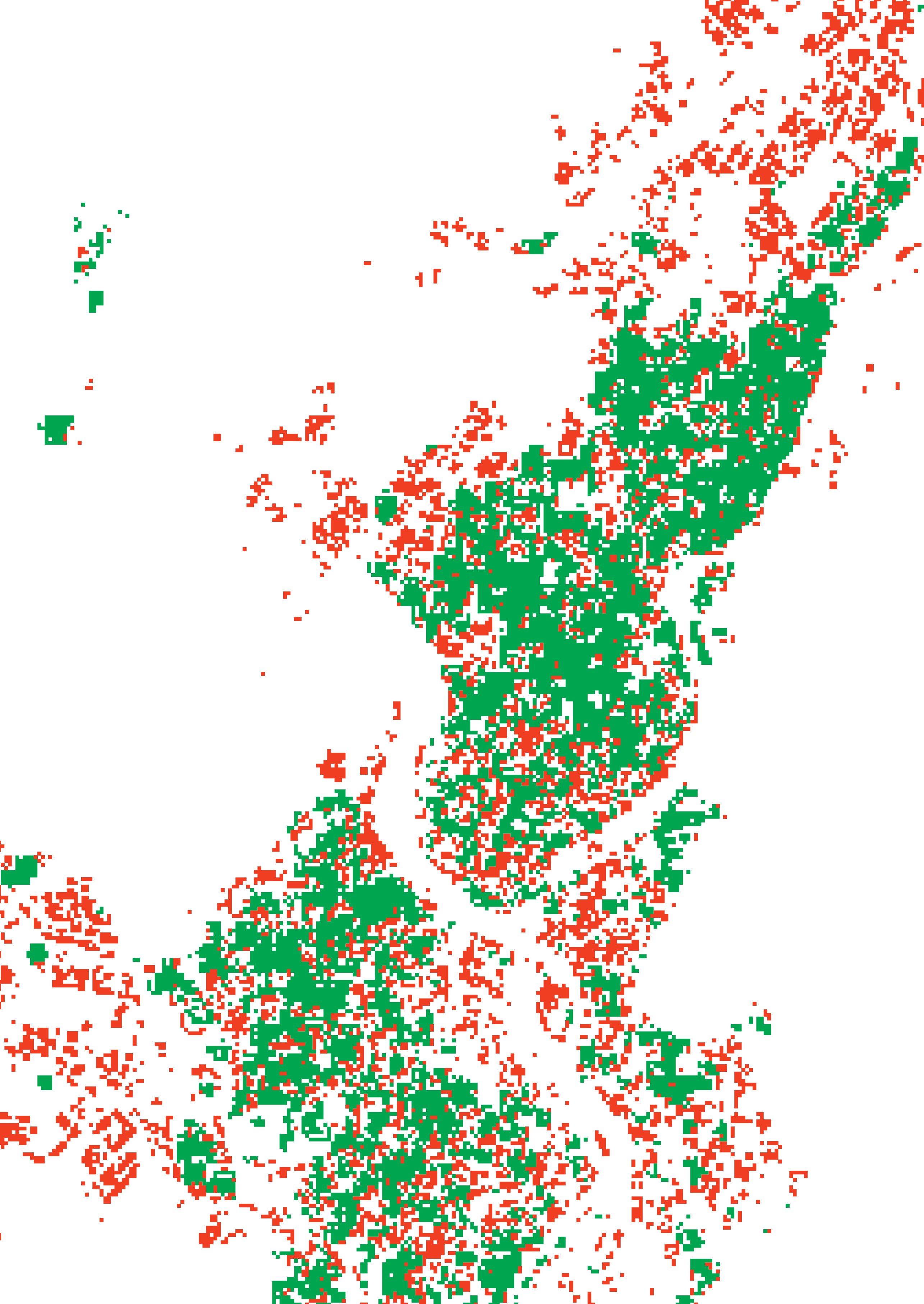
SPATIAL DIVERSITY AND SUSTAINABLE URBANISATION IN OMAN

AUREL VON RICHTHOFEN



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AUREL VON RICHTHOFEN

Für Ludovica und
Ferdinand (Nando)

sowie meine Geschwister
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Friedrich, Rose und Cécile.

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Spatial Diversity and Sustainable Urbanisation in Oman

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P A R T

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ABSTRACT

PART 0: ABSTRACT
KURZFASSUNG AUF DEUTSCH

Diese Dissertation untersucht die Konsequenzen der durch schnelles ökonomisches und demographisches Wachstum eingeleiteten und seit 1970 anhaltenden Urbanisierung in Bezug auf die räumliche Diversität in Oman. Bezugnehmend auf geographische, klimatische, ökologische, historische, soziokulturelle, politische und ökonomische Aspekte positioniert diese Dissertation Oman an einem kritischen Wendepunkt: Dessen räumliche Ressourcen sind stark beschränkt, ungleich verteilt, nicht zugänglich und asymmetrisch in Wachstums- und Konzentrationsprozesse eingebunden. Diese Arbeit verknüpft räumliche Diversität mit resilienter Landnutzung und nachhaltiger städtebaulicher Entwicklung unter Berücksichtigung des andauernden demographischen Entwicklungsdruckes einerseits und endlicher Raum-, Wasser-, Energie- und Materialressourcen andererseits.

Die Hypothese dieser Arbeit postuliert, dass ein differenziertes räumliches, zeitliches und strukturelles Verständnis räumlicher Diversität anhand von Landnutzungskarten, räumlichen Diversitätsindizes und Urbanisationsmodellen zu einer resilienten und nachhaltigen Form der Urbanisierung führt. Literaturstudien, Dokumentation vor Ort, Fernerkundung aufgrund historischer Satellitenbilder, Kartierung mittels Geo-Informations-Systemen und parametrisches städtebauliches Entwerfen sind Methoden dieser Dissertation. Die Arbeit untersucht gegenwärtige Urbanisationsmodelle in Oman in Bezug auf städtischen Metabolismus, urbane Nachhaltigkeit und räumliche Diversität. Die Landnutzungsveränderung wird auf nationaler, sowie in fünf regionalen und 18 lokalen Untersuchungsgebieten mittels Kartierungen dokumentiert. Die Dissertation stellt ‚Raum-Spezie' vor die sich durch Fernerkundung erkennen lassen und deren Verteilung mittels eines räumlichen Diversitätsindexes der lokalen Untersuchungsgebiete gemessen werden kann. Die Ergebnisse lassen den Schluss zu, dass eine ausgeglichene räumliche Diversität zwischen landwirtschaftlicher und urbaner Nutzung die besten Voraussetzungen für eine resiliente und nachhaltige räumliche Entwicklung gewährleistet. Diese Erkenntnisse fließen in vier städtebauliche Entwurfsstrategien, räumlich diverse und

ressourcenschonende städtebauliche Entwurfsstrategien ein, die wiederum in parametrische städtebauliche Modelle übersetzt werden. Diese parametrischen städtebaulichen Modelle unterstützen die Entwicklung von städtebaulichen Szenarien und die Visualisierung der resultierenden urbanen Form anhand von dreidimensionalen Modellen. Die Dissertation schließt mit einer Diskussion über räumliche Diversität als Ansatz einer resilienten und nachhaltigen räumlichen Entwicklung in Oman.

Schlüsselwörter:
Nachhaltige Urbanisierung; räumliche Diversität; Raum-Spezie; parametrische urbane Modelle, Oman.

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ABSTRACT IN ENGLISH

This dissertation examines the consequences of urbanisation triggered by rapid economic and demographic growth in Oman since 1970 on spatial diversity. By tracing geographic, climatic, ecological, historic, socio-cultural, political and economic aspects the dissertation positions Oman at a crucial turning point where spatial resources are limited, not evenly accessible and not symmetrically mobilised by processes of urban growth, extension and concentration. The dissertation links spatial diversity to resilient land use and sustainable urban development in light of ongoing demographic growth and depleting resources.

The hypothesis of this dissertation postulates that a differentiated spatial, temporal and structural understanding of spatial diversity in the form of land use maps, spatial diversity indices and urbanisation models can lead to a more resilient and sustainable form of urbanisation in Oman. The methods used are desk studies, field documentation, remote sensing with historic satellite images, geo-information systems mapping and parametric urban modelling. The dissertation reviews current urbanisation models in Oman in relation to urban metabolism, urban sustainability and spatial diversity. It then maps land use transformation processes across Oman at the national level, as well as focussing on four regions and 18 local samples. The dissertation postulates 'space species' that can be discerned through remote sensing and establishes a spatial diversity index for these local samples. The findings suggest that a balanced spatial diversity for both agricultural and urban land uses is the optimal land use configuration for a resilient and sustainable spatial development in Oman. These insights result in four urban design strategies in response to the specific regional conditions. The urban design strategies – spatially diverse and resource efficient – are translated into parametric models. These parametric urban models allow to develop urban design scenarios and visualise urban form in 3D models. The dissertation closes with a discussion of spatial diversity as a measure of sustainable and resilient development in Oman.

Key Words:
sustainable urbanisation; spatial diversity; space species; parametric urban models; Oman.

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All tables were produced by the author. Sources are mentioned when tables are based on previous work.

LIST OF ACRONYMS

BA	Built Area
BAT	Al Batinah region in Oman
BTI	Bertelsmann Political Transformation Index
CA	Circulation Area
CAD	Computer-Aided Design
CE	CityEngine, procedural design software
CGA	Computer Generated Architecture (CE)
CO2	Carbon Dioxide
DEM	Digital Elevation Model (GIS)
ESA	European Space Agency
ETH	Eidgenössische Technische Hochschule Zürich
FAR	Floor Area Ratio
GA	Green Area
GADM	Global Administrative Areas (GIS)
GCC	Gulf Cooperation Council
GDP	Gross Domestic Product
GIS	Geo-Information System
GPR	Gross Plot Ratio
GPS	Global Positioning System
GUTECH	German University of Technology in Oman
H	Shannon Index
HMAX	Shannon Index (maximum)
ISU	Institute of Sustainable Urbanism (TUB)
ITC	Integrated Tourism Complex (Oman)
LNPI	Natural Logarithm of PI (Shannon Index)
LRHD	Low-Rise High-Density
MCA	Muscat Capital Area
MOH	Ministry of Housing (Oman)
NGO	Non-Governmental Organisation
NIZ	Nizwa region in Oman
OBIA	Object-Based Image Analysis (GIS)
ONSS	Oman National Spatial Strategy
PA	Plot Area

PI	Proportion of Individuals (Shannon index)
QGIS	Free and open-source cross-platform desktop geographic information system (GIS)
ROI	Region of Interest (GIS)
RQ	Research Question
SAL	Salalah region in Oman
SCP (GIS)	Semi-Automatic Classification Plugin
SCP (OMAN)	Supreme Council of Planning (Oman, since 2012)
SCTP	Supreme Committee of Town Planning (Oman, until 2012, then SCP)
SQU	Sultan Qabous University
SRTM	Shuttle Radar Topographic Mission (GIS)
TIF	Tagged Image (file) Format (GIS)
TUB	Technische Universität Braunschweig
UN	United Nations
UN HABITAT	United Nations Human Settlements Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UPAD	Department of Urban Planning and Architectural Design (Gutech)
UPC	Abu Dhabi Urban Planning Council
USGS	U.S. Geological Survey
WTO	World Trade Organisation

USE OF ARABIC TERMS

Arabic terms that designate a particular concept and have no immediate translation into English such as 'falaj' or 'willayat' are explained in their context. Arabic places and Arabic names are transliterated from Arabic into Roman script as used in Oman. Not all names have been harmonised in Oman and a certain degree of confusion persists, for example with place names like "Mutrah", "Matarah" and "Muttrah" that designate one and the same district of Muscat Capital Area (MCA). This dissertation follows the transliteration commonly used in Oman and Anglophone literature. Geographic names follow the US National Geospatial Intelligence Agency records, where the generic, common name is preferred for simplicity reasons and ease of reference. [1] In this dissertation the approved name "Masqaţ" gives way to the common name "Muscat" when it comes to a city widely known under that transliteration. Since the scope of this dissertation is the recent urbanisation of Oman all dates are entered in the Gregorian calendar format and not in the Hijri calendar format.

ACKNOWLEDGEMENTS

This dissertation grew out of research interest in understanding and shaping sustainable urbanisation during my time as assistant professor at the German University of Technology (GUtech) in Oman from 2010–14. The dissertation was anchored at the Institute of Sustainable Urbanism (ISU) at Technische Universität Braunschweig in 2013. It was shaped in dialogue with many colleagues and friends during my time as senior researcher at the Future Cities Laboratory in Singapore since 2014. During this journey I was fortunate to meet exceptional people that offered support, advice, critique and lasting friendship without which it would have not been possible to accomplish this dissertation. I would like to thank a few of them here and hope that those I accidentally left out will notice their impact as they read the text.

I would like to thank Prof. Dr. Sonja Nebel, my mentor and colleague in Oman, for inviting me to become co-investigator on a research project entitled '*Towards Sustainable Urbanisation Patterns in Oman*' in 2011. This research project was in many ways the foundation of this dissertation and a fantastic point of

1 US National Geospatial Intelligence Agency, "GeoNames Search – Oman."

departure as the joint conference and exhibition in 2014 and publication in 2016 opened more research questions than we could answer. I would like to thank Prof. Dr. Vanessa Miriam Carlow, my thesis supervisor and director of ISU, for recognising the potential of this topic and generously supporting the thesis from the beginning. I would also like to thank Junior Prof. Dr. Reinhard König for reviewing the thesis.

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My deepest respect goes to Prof. Emeritus Dr. Fred Scholz, in Berlin, whose seminal work *'Muscat – Eine Arabische Stadt'* of 1990 was the starting point for my own studies on urbanisation in Oman. I would also like to remember the late Prof. Dr. Maurizio Tosi, former director of antiquities in Oman, with whose brilliant mind helped me to understand dynamic cultural links and networks of Oman and the Gulf across time and space.

I wish to thank my parents, Fee and Wolfgang, for their encouragement. My father was patient enough to read the manuscript – though any remaining mistakes are entirely my own responsibility. This thesis is dedicated to my wife Ludovica, our son Ferdinand (Nando) and my siblings Leontine, Lovis, Anne-Madeleine, Friedrich, Rose and Cécile. ●

P A R T

I

HYPOTHESIS AND STATE OF RESEARCH

PART 1: HYPOTHESIS AND STATE OF RESEARCH
HYPOTHESIS

This dissertation explores spatial diversity as a new approach to sustainable urbanisation in Oman. It examines the links of land use transformation and spatial diversity. It traces land use transformation triggered by rapid economic, demographic and urban growth in Oman since 1970. It argues that urban sustainability is constrained, even more essentially than by the presence or absence of water, by one key non-renewable resource – space. Sustainability constraints are not just imposed by the physical dimensions of space itself being finite yet relatively abundant in a desert country like Oman (which seems to be a paradox at first sight), but by the potential of this space to provide services and the costs to activate it. These services and costs are not just limited to economic aspects, but comprise all dimension of urban sustainability: social, political, ecological, economic and spatial. The study of historic settlement patterns such as oasis towns and irrigated landscapes shows a higher degree of spatial diversity than in modern settlements indicating that spatial diversity decreased as urbanisation set in across Oman (and elsewhere). Since the beginning of modernisation triggered by the discovery and exploitation of oil in the late 1960s, Oman is considered to be at a crucial turning point where spatial resources are limited, not evenly accessible and not symmetrically mobilised by processes of urban growth, extension and concentration. The dissertation links spatial diversity to resilient land use and sustainable urban development in the light of ongoing demographic growth and depleting resources. It argues that a decreasing spatial diversity is a threat to the future potential of sustainable urbanisation and agriculture, two aspects that are linked with Oman's demographic, energetic, economic and ecological challenges. The hypothesis of this dissertation is that spatial diversity can

- be distinguished, mapped and measured at various scales (national, regional, local);
- provide information on the degree of sustainability land-transformation can achieve; and
- support alternative urban design strategies and evaluate them.

The hypothesis of this dissertation postulates that an integrated spatial, temporal and structural understanding of spatial diversity in the form of land use maps, spatial diversity indices and informed urbanisation models can lead to a new approach to urban sustainability and to a more resilient and sustainable form of urbanisation in Oman.

RESEARCH QUESTIONS

The research questions deriving from this hypothesis are:

– How can we discern, map and measure spatial diversity at various scales in Oman considering the complex and multi-dimensional processes that unfolded since 1970?

  This question will be answered by literature review on urbanisation in Oman to determine observation criteria for spatial diversity, the identification of the key interlinked aspects of housing and agriculture, followed by remote sensing using satellite images to map spatial diversity.

– How do we need to adapt current concepts of sustainable urbanisation to include spatial diversity?

  This question will be answered by a review and critique of the urban sustainability discourse exemplified by contemporary urban design case studies in Oman, followed by an index of spatial diversity to be applied to the remote-sensed observation sites in Oman. This will reveal degrees of spatial diversity across Oman for the selected sites.

– How can we develop alternative urban design strategies based on a new approach to urban sustainability focussing on the key interlinked aspects of housing and agriculture?

  This question will be answered by the development of parametric urban models that allow to create residential and agricultural urban design scenarios for four regional case studies. Besides spatial three-dimensional information – the urban and agricultural form – the parametric models yield information about spatial diversity and allow to assess them as valid alternatives to the status quo.

The hypothesis and research questions relate to a theoretical discourse that links spatial diversity to resilient land use and sustainable urban development in the light of ongoing demographic growth and depleting resources. It mobilises the discourses around:

– the *'Production of Space'*, 2
– *'Urban Metabolism'* as a dynamic system of stocks and flows that can be described as 'anthropogenic metabolisms' on urban landscapes, 3
– and takes a critical look at *'sustainable development'* and *'urban sustainability'*, 4
– to develop the concept of *'spatial diversity'* in analogy to biodiversity. 5

The concept of spatial diversity is then used to evaluate land use transformation, calibrate urban development models and propose future urban design scenarios for Oman.

– Two key aspects relevant to land used transformation are singled out from the literature review on urban studies in Oman: Housing and Agriculture, 6
– Remote sensed maps on a national scale and covering the last 40 years are used to describe the spatial and temporal dynamics of land use transformation in Oman, 7 and
– Parametric urban models are used to develop alternative urbanisation models. 8

2 Lefebvre, *La Production de l'espace*; Schmid, *Stadt, Raum und Gesellschaft*.
3 Baccini, Oswald, and Michaeli, "The Synoikos Method"; Oswald, Baccini, and Michaeli, *Netzstadt*; Baccini, *Metabolism of the Anthroposphere*.
4 Gunder, "Sustainability"; Swyngedouw, "Impossible' sustainability' and the Postpolitical Condition"; Berger, "The Unsustainable City"; Mössner, "Sustainable Urban Development as Consensual Practice."
5 Dasmann, *A Different Kind of Country*; Benton, "Origins of Biodiversity."
6 Scholz, *Muscat, Sultanat Oman*; Belgacem, "Is Littoralization Reconfiguring the Omani Territory?"; Al Gharibi, "Urban Growth from Patchwork to Sustainability Case Study: Muscat"; Al Shueili, "Towards a Sustainable Urban Future in Oman: Problem and Process Analysis"; Nebel and von Richthofen, *Urban Oman – Trends and Perspectives of Urbanisation in Muscat Capital Area*.
7 Bhatta, *Analysis of Urban Growth and Sprawl from Remote Sensing Data*
8 Koenig and Bauriedel, "Computergenerierte Strukturformen v.01"; Batty, "Urban Modeling"; Batty, "A Theory of City Size"; Bettencourt, "The Kind of Problem a City Is"; Zünd, "A Meso-Scale Framework to Support Urban Planning."

STRUCTURE OF THE THESIS

This thesis is structured into six parts plus an appendix:

- **Part 1** opens the research project with the hypothesis and research questions around spatial diversity followed by a theoretical contextualisation through a literature review of the different steps of developing and applying spatial diversity in Oman.

- **Part 2** describes how spatial diversity transformed over the past 50 years of modernisation in Oman. This is a critical commentary that links literature review and the author's own investigations through field work to determine the necessary observation lenses and to underline thematic focus areas of housing and agriculture.

- **Part 3** discusses methods and data availability and describes the in-depth process of remote sensing, the spatial diversity index formation and the parametric urban design modelling approach.

- **Part 4** presents and discusses the findings of the remote sense maps of Oman at national, regional and local scales together with the spatial diversity index.

- **Part 5** proposes four urban design strategies that address the unbalanced and unsustainable urbanisation in four regions in Oman. The resulting urban designs are evaluated and discussed.

- **Part 6** discusses the thesis contribution and closes with a critical outlook to further research.

LEFEBVRE'S 'PRODUCTION OF SPACE'

If we want to develop a concept of spatial diversity, we first need to discuss space as a concept. The discourse on space in architecture and by extension in urban design, the complex process of adoption, evolution and critique of the term, has been reconstructed by Forty. 9 Forty argues that space is indeed a constructed concept of the 20th century and tightly linked to modernism, prior to which space did not matter fundamentally for architects and urban designers in contrast to architectural categories such as material or tectonic, for instance. Forty argues that architects (and urban designers) necessarily conceive of space as a concept and as its manifestation. Forty traces this duality of space back to Hegel's discourse on aesthetics and the idea of space being "*the independent embodiment of an idea [and the idea itself]",* additions by the author. 10 This duality entails several considerations that will guide this dissertation and are expressed by Lefebvre: Space can be conceived as a concept and as the manifestation of a process. 11 *"Lefebvre's starting point is the neglect, not only by philosophy but by all human sciences, of what 'space' is: the mind thinks of space, but it does so within a space, a space that is at once both conceptual, but also physical, a space as embodiment of social relations, and of ideology."* 12 Next to the duality of *'espace perçu et espace conçu'* ['perceived and conceived space', translation by the author] Lefebvre proposes positions the production of space in a milieu the *'espace vécu'* ['lived space', translation by the author]. This triade entails that space is on a constant dialogue with the agents that engage, design, shape, transform and 'produce' it. Lefebvre frames the production of space as a social product. Space is the mirror and result of the social processes. 13 These agents, workers or citizens in the case of an urban setting, thus play a crucial role in the productive process and have a certain responsibility towards space as their actions will determine the conditions of production and therefore the quality of space. This production does not literally produce new space in the sense of additional land to built-upon, but describes the process of 'commodification'

9 Forty, *Words and Buildings*.
10 Hegel, *Aesthetics*, 631.
11 Lefebvre, *La Production de l'espace*.
12 Forty, *Words and Buildings*, 271.
13 Bertuzzo, "During the Urban Revolution : 'Conjunctures' on the Streets of Dhaka."

or transformation of existing 'social space' into usable, accessible and malleable 'abstract space'. Lefebvre is critical about this process as it is projected, shaped and determined by planners and hegemonists at the expense of social space. Once stripped of life-sustaining social functions this abstract space is commodified and sold. According to Lefebvre pre-industrialised societies kept commons as 'social space'. In Lefebvre's own terms social space is both "*work and product – a materialization of 'social being*'". 14 Any production process would not fundamentally alter the quality of the common. Multiple actions, interactions and reactions between inhabitants and workers in daily life lead to by simply inhabiting the social space. Industrialised societies on the other hand witness a gradual commodification of commons into spaces subject to capitalism. Lefebvre alerts us to this process which, if understood, can be resisted and reversed. Based on Hegel and following Marxist theory, Henri Lefebvre developed the concept of 'production of space' in 1974. His writings were received by a large audience in the West but were only translated into English in 2003 15. Lefebvre identifies the tendency of modern societies to reduce the complexity of social space to a commodity, namely 'abstract space'. *"Abstract space, which is the tool for domination, asphyxiates whatever is conceived within it. [...] This space is a lethal one which destroys the historical conditions which gave rise to it, its own (internal) differences, and any such differences that show signs of developing, in order to abstract homogeneity."* 16 According to Lefebvre architecture and by extension urban planning play a vital role in the production of social space and subsequent commodification into 'abstract space'. Lefebvre argues that space and society are inseparably interlinked and revealed through a process of 'production'. Space is not the neutral canvas on which architects, politicians or industrialists operate, it has already been produced by the various citizens that engage with it: *"This space has nothing innocent about it: it answers particular tactics and strategies; it is, quite simply, the space of the dominant mode of production, and hence the space of Capitalism."* 17 The precise techniques (drawings, plans, models, visualizations) invented by architects and urban designers cater to the established power-models that abstract complex social space into abstract space. Space as embodiment of social relations leads to the conditions of production of space in Marxist terms. Forty describes the socio-cultural consequences of spatial abstraction as 'flattening': *"Within abstract*

14 Lefebvre, *The Urban Revolution*, 101.
15 Lefebvre, *The Urban Revolution*.
16 Lefebvre, 370.
17 Lefebvre, 360.

space, its occupants find that they themselves become abstractions, as 'users', and are unable to see space other than in the mutilated, sliced-up form presented to them; and while the space they find themselves within appears to be coherent, and seems transparent, this too is part of the flattening and reduction achieved by abstract, mental space." 18 The analysis of the conditions of production of space poses fundamental problems to the disciplines involved in them: *"For Lefebvre all scientific and artistic disciplines are involved with space. […] At the same time, no individual discipline is capable of giving a satisfactory account of social space, because of the tendency of each discipline to render it into an abstraction appropriate to its own purpose."* 19 The work of the designer (architect and planner) and as much as the critical researcher is constituted through the space in which they operate.

Lefebvre's concept of 'production of space' can be used for an interdisciplinary approach to the problem of production and transformation of space; one that does not render the process abstract or opaque, but rather explains, maps and presents the conditions, processes and agents of transformation, adding a dimension of operability onto space otherwise absent. Lefebvre identifies the production of space in urban settings as a process intrinsically linked to the productive labour of its citizens. He claims that the derivates of spatial production, such as usufruct of land, speculation and urban transformation benefit few and need to be returned to the majority that contributed to the production in the first place. Lefebvre's concept offers a first line of critique: The homogenising aspect of this commodification implies the erasure of difference, the exclusion of alternatives, the impossibility of transformation and the exclusion of the possibility of reversal to a previous spatial state – a process that is visible as the 'Renaissance' development strategy in Oman. While Lefebvre deplores the transformation from social space towards abstract space his theory also allows to develop an operational strategy: to envision the reverse process of commodified production of space. This does not mean a deconstruction of the term but rather a reversal of the conditions of production. A production of space adjusted to the needs of a society that defends social space.

18 Forty, *Words and Buildings*, 274.
19 Forty, 274.

EXTENDED URBANISATION

A process of extended, planetary urbanisation unfolds at all scales, from the local to the regional to the global, and in multiple dimensions of resources, energy and human activity. This process of extended urbanisation has been largely overlooked until recently by architects, urban designer and urban geographers because of its sheer complexity. Lefebvre's concept of production of space offers an entry point to describe a global process of urbanisation that has also reached Oman. The production of space requires agents, be they individuals or larger communities, and an observation perimeter that can be a city, district, country or supra-national region. The various manifestations of the extended urbanisation process can then be traced back to actors or actor groups and observation boundaries or so called hinterlands, whereas the production of space is revealed ('hinterland' German = land beyond, behind). The all-encompassing aspect of urbanisation no longer coincides with historic city centres nor with administrative boundaries is stated by Soja and Kanai. *"Urbanism as a way of life, once confined to the historical central city, has been spreading outwards, creating urban densities and new 'outer' and 'edge' cities in what were formerly suburban fringes and green field or rural sites … [I]n some cases city regions are coalescing into even larger agglomerations in a process that can be called 'extended regional urbanisation'."* 20 It becomes evident that on the large scale of cities, districts, countries or supra-national regions actor groups and their behaviour are becoming increasingly complex, conflicting-laden and competitive. Such arenas of actor (-groups) and multi-scale regions can be summarised under the concept of territories. Schmid and Brenner propose to observe the various production processes of space in areas of increasingly interconnected urban systems. 21 These systems connect, overlap and by extension reach around the globe. To position their argument Schmid and Brenner clarify *"The urban and urbanisation are theoretical categories. The urban is not a pre-given, self-evident reality, condition or form – its specificity can only be delineated in theoretical terms, through an interpretation of its core properties, expressions or dynamics."* 22 The distinction of the urban as theoretical category makes it possible to divorce it from traded notions of the urban and position the urban as dynamic concept subject to interpretation. *"The urban is not a universal form but a historical process. In contrast to inherited concepts of the urban as a definitionally fixed*

20 Soja and Kanai, "The Urbanization of the World," 55.
21 Schmid, *Stadt, Raum und Gesellschaft*; Brenner, *Implosions/Explosions*.
22 Brenner and Schmid, "The 'Urban Age' in Question," 749.

unit or static form, its meanings and expressions must be understood to evolve historically in relation to broader patterns and pathways of global capitalist development." 23 By observing urban regions across the world – at different scales and across time – Brenner and Schmid describe urbanisation as a multidimensional dynamic process. *"Urbanisation involves both concentration and extension. Once urbanisation is seen as a process that transforms diverse zones of the world, another entrenched methodological tendency must be superseded, namely the exclusive or primary focus of urban scholars on agglomerations, the densely settled zones (cities, metropolitan regions, megacity regions, and so forth) in which population, economic activities and infrastructural systems are clustered."* 24 This statement also removes the primacy of 'densely settled zones' as worthy of research. Applied to the case study Oman, this calls for an extensive observation of the whole territory, including non inhabited and semi-inhabited parts such as deserts, mountains and agricultural areas. It also resolves a lingering side-problem of the artificial but still prevalent differentiation of rural and urban. Within this dissertation the term rural will not be used in opposition to urban. In a similar line of thought, we will not enter into a discussion of sub-urban, peri-urban or similar terms. Agricultural space and residential space will be considered simply as urban. Brenner and Schmid conclude that the process of urbanisation has reached total, planetary scale, but needs to be nonetheless differentiated for each case study and territory as the processes of urbanisation are highly unequal and uneven: *"Urbanisation has become a planetary phenomenon. Today, urbanisation is a process that affects the whole territory of the world and not only isolated parts of it. The urban represents an increasingly worldwide, if unevenly woven, fabric in which the sociocultural and political-economic relations of capitalism are enmeshed. This situation of planetary urbanisation means that even socio-spatial arrangements and infrastructural networks that lie well beyond traditional city cores, metropolitan regions, urban peripheries and peri-urban zones have become integral parts of a worldwide urban condition. ... There is, in short, no longer any outside to the urban world; the non-urban has been largely internalized within an uneven yet planetary process of urbanisation."* 25 They further argue that the socio-spatial dimensions of urbanisation are polymorphic, variable and dynamic. Urbanisation is a dynamic process that involves both concentration and extension and produces new differentiations. *"Urbanisation is*

23 Brenner and Schmid, 750.
24 Brenner and Schmid, 750.
25 Brenner and Schmid, 751.

a process of constant transformation and leads continuously to the production of new urban configurations and constellations. Zones of urbanisation, and the urban condition more generally, should not be treated as homogeneous – neither in the contemporary era nor during earlier historical periods. Rather, urbanisation processes produce a wide range of socio-spatial conditions across the world that require contextually specific analysis and theorization." 26

The concept so developed claims that the transformative processes of cities on their hinterland produce urban conditions, that these processes have by now reached a planetary scale, and therefore, by definition apply to the Arab Gulf cities as well. The apparent beauty of the concept relies in the resolution of the dichotomy of urban and rural spaces, in fact a Euro-centric problematic, and by provision of a new global definition of the urban that is found in an ongoing entropic process of urbanisation. Accordingly, the concept may be proven for all urbanising areas by simply studying the process of urbanisation. As a theoretical framework, the concept of extended urbanisation helps to define ongoing urbanisation and land use transformation processes in Oman. It offers an entrance point to describe agents and their competing interests in the production of space at a regional level. It can be used to describe hinterlands to urban centres that are in most cases different from existing administrative boundaries. A first attempt to study the extended urbanisation across the territory of Oman according to the method developed by Brenner and Schmid was a seminar trip to Oman lead by ETH Zurich and hosted by the German University of Technology Oman (GUtech). 27 The resulting publication on the "Territory of Muscat and Oman" in 2013 contained a compilation of materials collected during the study trip. 28

Within this definition the territory undergoing urbanisation is conceived as 'constitutive outside' anticipating its transformation by contributing to the Urban. Recent post-colonial critiques of the concept highlight that urban conditions found outside of Western rural-urban conditions radically defy the concept of 'planetary urbanisation' radically. Roy develops a strong argument for urban conditions found in her case study of Calcutta that she calls 'real/radical outsides'. 29 These spaces cannot be described

26 Brenner and Schmid, 751.
27 von Richthofen, "Focal Point for ETH Studio Basel in Oman."
28 Jovanovic, Meili, and Diener, "Muscat and Oman – Restructuring a Desert Landscape."
29 Roy, "Who's Afraid of Postcolonial Theory?," 201.

as rural nor aspiring to become urban. Instead, these spaces become entities of their own, outside of a conceptual framework of planetary urbanisation. This thesis aims to test Roy's concept regarding large parts of the nation states in Arab Gulf countries that are covered by deserts. While Brenner and Schmid would argue for the conceptualisation of these desert spaces as urban hinterland that contains vast amounts of man-made infrastructure such as roads, electric power lines, pipelines, oil wells, quarries, depots, military zones, etc. and thus support the urban, this thesis argues in line with Roy and demonstrates that these spaces are subject to a contrasting logic originating in nomadic, tribal societies and were never conceived as rural in the past nor will they ever be conceived as urban in the future. The mappings in this thesis challenge Lefebvre's dimensional model that constitutes the urban to prove that these spaces cannot fit into the schemata of planetary urbanisation. Looked at from a post-colonial perspective these desert spaces form a spatial category radically outside and independent of the urban. These desert spaces that are neither suitable for sustainable urbanisation nor agriculture constitute more than 95% of the Arab Gulf territory. This has substantial consequences for the conception of urbanisation of the Arab Gulf cities and their future development. It overturns the prevailing narrative of abundant space for urbanisation and, in consequence, sustainable development in the region based on the assumption that urban expanse is not hindered by spatial limits. Against the backdrop of the 'real/radical outsides' of the desert, this dissertation looks at two specific aspects of extended urbanisation, due to their relevance for the concept of spatial diversity in Oman, namely housing and agriculture.

URBAN METABOLISM

As described by Lefebvre, the production of urban space is a perpetual process driven by various stake holders. [30] Brenner and Schmid apply and scale Lefebvre's concept to urbanising regions. Urban systems and their hinterlands are dynamic. Their activity can be measured in metabolic rates of stocks and flows of humans, energy and materials. 'Metabolism of the Anthroposphere: Analysis, Evaluation, Design' by Baccini describes metabolistic systems created by mankind. [31] A discussion of metabolic rates contributes to the spatial diversity index for Oman as discussed in this dissertation. These systems are based on the fundamental

30 Roy, 201.
31 Baccini, *Metabolism of the Anthroposphere.*

physical equilibrium of energy and material within a confined system where no material goes to waste and all energy eventually turns into heat due to thermodynamic laws. Each metabolic model uses an observation perimeter, a spatial extent, onto which the metabolic model applies. The earth is depicted as such a system that is relatively impermeable to material input and output, with a constant influx of solar and output of thermal energy. The system boundary for the whole planet is a physically closed system: the outer atmosphere. The system 'planet earth' consists of three different spheres: the geosphere, the biosphere and the anthroposphere that colonises the other spheres. All spheres are interrelated and exchange material and energy. The specific strength of urban metabolism is that it allows to quantify the rates of exchanges of material and energy, stocks and flows between spheres. Material and energy are transformed within the spheres by metabolic processes resulting in the discharge of material and energy as emissions or the accumulation and deposition in stocks. According to Baccini, the concept of sustainable (urban) development can be attributed to von Thünen (1826). [32] Von Thünen's model of concentric circles corresponding to travel distances feasible by contemporary technology radiating from city cores anticipate a concentric, self-sufficient solar city. Thünen's idea was influential on both the dichotomy of rural-urban, an ideal self-sufficient equilibrium and the size of its supporting area as spatial territory or abstract footprint. Brenner and Schmid underline the idea of stocks and flows in their description of urbanising systems as dynamic entities: *"Though largely ignored or relegated to the analytic background by urban theorists, such transformations – materialized in densely tangled circuits of labor, commodities, cultural forms, energy, raw materials and nutrients – simultaneously radiate outwards from the immediate zone of agglomeration and implode back into it as the urbanisation process unfolds."* [33] Anthropogenic activities, including urban metabolism, can be modelled using Baccini's metabolism model and measured with transmission coefficients. [34] The metabolism model can be subdivided into smaller entities and applied to all metabolic processes in the anthroposphere (SEE FIGURE 1). Urbanisation is a main contributor to the anthroposphere as the place of basic metabolic processes of human activities is: to nourish, to clean, to reside & work, to transport & communicate. [35] The city is modelled with private households as the 'primary cell' of observation. These households account for

32 Baccini, 5.
33 Brenner and Schmid, "The 'Urban Age' in Question," 750.
34 Baccini, *Metabolism of the Anthroposphere*, 17.
35 Baccini, 29.

80% of the stocks and flows of a developed society. [36] The model can be applied to the scale of a region, a city and its adjacent rural areas. Baccini uses hinterland as a geographic term to describe the area necessary to support the urban. For the metabolic model it is a technical term to describe everything that is outside of the systems boundary. This boundary has to be carefully determined to ensure valid results. Once a system boundary and its sub-sets are defined we can quantify the stocks and flows based on Baccini's metabolic approach. The rural does not coincide with the hinterland. The hinterland might be a larger and more remote area that is required to support the object of observation (household, city or region). The increasing urbanisation propels metabolic processes within societies. [37] The accelerated dynamic of material flows is a symptom of anthropogenic metabolism. In particular if the import of materials exceeds the export of stock, accumulation occurs. In contrast to biospheric processes linear material flows dominate: There is no recycling of materials and energy. If anthropogenic flows exceed geogenic flows resource scarcity occurs [38] and if anthropogenic flows exceed geogenic stocks, the result is pollution. [39] Anthropogenic processes position urbanisation as a process of global conversion of 'nature' into designed and constructed environment. Resource scarcity is the constraint to unhindered development. Climate change is a threat to this development and might yield higher costs in the future (maintenance, etc). Sustainable development is the solution and modus to steer the process of urbanisation developed in a 'Netzstadt' (network-city in German, translation by the author); [40] or in a new urban model/system called 'Metaland'. [41]

36 Baccini, 31.
37 Baccini, 44.
38 Baccini, 77.
39 Baccini, 146.
40 Baccini, Oswald, and Michaeli, "The Synoikos Method"; Oswald, Baccini, and Michaeli, Netzstadt.
41 Baccini, *Metabolism of the Anthroposphere*, 174.

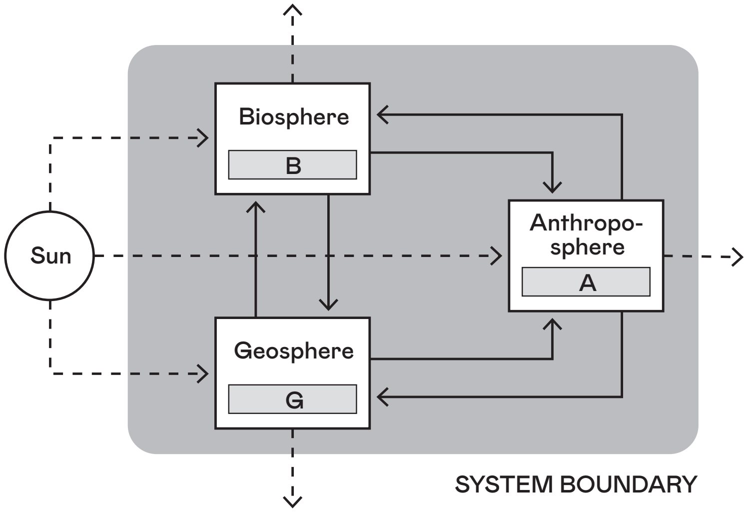


FIGURE 1
Diagram of the earth as metabolic system, based on P. Baccini.

Baccini's model supports the description of the increasing complexity and the changes in stocks and flows of urban infrastructural spaces and agriculture. In its essence the model is an accounting tool. This allows to recognise streams, deposits and, of course, those who initiate them. As Baccini concludes, early recognition of environmental disruption is possible through the development and understanding of metabolisms for urban areas. This can be used to support political strategies. 42

URBAN SUSTAINABILITY

This section aims to develop a differentiated view on urban sustainability. The term needs to be discussed against the backdrop of an evolution of sustainability stemming from economy towards the rise of ecological thought. Urban sustainability relates to an intrinsic human activity: The transformation of the environment most notable in the creation of cities. This activity impacts all biomes of the planet, though to varying degrees and asks the question of compatible use of resources not just amongst present and future humans, but amongst all creatures of the planet.

A more general definition of urban sustainability includes social, economic, ecological, physical and political dimensions contributing to a lasting and resource-conscious urban development. This

42 Baccini, 361.

view leads to the creation of various sustainable development indices and targets, though not without the critique that this economic co-option of sustainability under the term of sustainable development is in fact a continuation of the capitalist exploitation model. 43 Finally, the aspect of space for urbanisation is discussed in particular as a resource and dimension of urban sustainability. Due to its status as a finite resource it deserves special attention. Space, considered as a mere physical quantity, is not per se sustainable (or not). Returning to Lefebvre's concept of production, the conditions that give rise to it matter and are manifested in a new quality: Spatial diversity as explained in the next section.

Sustainability and Ecology: Sustainability originates in forestry, where it was developed as a model to assess the natural rates of replenishment to manage timber stocks. It is essentially an economic concept that endeavours to reach an optimal state of production and to conserve it (see: 'Nachhaltigkeit' coined by von Carlowitz in 1732, reprinted). 44 Von Thünen applied economic sustainability to spatial systems and explored the opportunity costs of production arising within concentric distances from a hypothetical urban centre. 45 Both concepts can be applied to all systems that use resources or transform them. In light of depleting resources and environmental degradation, sustainability attained first an ecological and then a political dimension. These dimensions relate to the use of energy, material and space, and to whether these can be replenished at the rate at which they are being used. Ernst Haeckel coined the term ecology in 1868. 46 It originates in the ancient Greek word 'Oikos' which refers to 'household, family or agricultural unit' encompassing the arable land, the built structure, livestock and its residents, labourers and slaves. This complex unit needed to manage its resources economically and within the 'balances of nature'. 47 Here the economic aspiration of sustainability overlaps with the natural principle of self-preservation of ecology. Haeckel expands the concept of 'Oikos' to all biological systems, thus forming the discipline of ecology.

43 Mössner, "Sustainable Urban Development as Consensual Practice," 980; Cummings and von Richthofen, "Urban Sustainability as a Political Instrument in the Gulf Region Exemplified at Projects in Abu Dhabi.," 260.
44 von Carlowitz, *Sylvicultura oeconomica*.
45 von Thünen, *Der Isolierte Staat in Beziehung Auf Landwirtschaft Und Nationalökonomie Oder Untersuchungen Über Den Einfluss, Den Getreidepreise, Der Reichtum Des Bodens Und Die Abgaben Auf Den Ackerbau Ausüben*.
46 Haeckel, *Natürliche Schöpfungsgeschichte*.
47 Egerton, *Roots of Ecology*.

In “The Ecological Context” McHale places man in the context of a ‘bio-sphere’ from where all material and energy inputs can be charted in relation to anthropogenic effects on the environment. The diagram sketched by McHale is a circular closed system, based on finite resources and within a confined topographical space of planet earth. [48] McHale argues that an ‘ecological redesign’ is necessary to answer no lesser questions than “*What are the optimal conditions for human society on earth? [...] What are the physical limits and constraints in the overall ecosystem? [...] What are the relevant human limits? [...] What are the irreplaceable resource limits?*” [49] Despite its anthropocentric viewpoint McHale’s theory contains all the elements of the sustainability argument defined in the Club of Rome report suggesting that a present generation should use only as much resources as can be replenished naturally during the time-span of use so that the same resources are left for the next generation to use. [50] During the second half of the 20th century environmental degradation, economic crisis and growing social inequality gave rise to the ecological movement such as represented by the Brundtland report: [51] seeking a state of optimal societal conditions, acknowledgement of physical and human limits, managing irreplaceable resources. Sustainability as a process of change has been recognised as early as 1987 in the Brundtland Report: *„Sustainability is not a fixed state of harmony, but rather a process of change, in which the exploitation of natural resources, the direction of investments, the orientation of technological development, and institutional change are made consistent with future as well as with present needs.”* [52]

The link between globalisation, human activity and cities in particular became evident approximately 10 years ago. [53] *“The increasing awareness of urban environmental considerations within debates about urban sustainability has consequently been mirrored by a growing concern among urban geographers with questions of urban environmental justice”*. [54] Biological ecology, in principle encompassing human activities and their impact on the environment, for a longtime ignored the city as a place worth studying. [55] In this

48 McHale, *The Ecological Context*, 29.
49 McHale, 167.
50 Meadows and Club of Rome, *The Limits to Growth; a Report for the Club of Rome’s Project on the Predicament of Mankind.*
51 World Commission on Environment and Development, *Our Common Future.*
52 World Commission on Environment and Development.
53 Grimm et al., “Global Change and the Ecology of Cities.”
54 Whitehead, “Sustainability, Urban,” 111.
55 McDonnell, Hahs, and Breuste, *Ecology of Cities and Towns.*

discourse, ecology is not to be confused with nature, a romantic concept that is distinct of, and opposite to human. In light of all encompassing global human activity, the concept of ecology needs to be rethought. 56 McDonnell coined 'Urban Ecology' as a new discipline of ecology. 57 This biological 'urban ecology' can then be linked to urban sustainability 58 or further to an *'Ecological science and transformation to the sustainable city'*. 59 Pickett postulates that: *"Urban ecosystem services, urban metabolism and urban political ecology to forge new thinking to transition from the sanitary city of the twentieth century to the sustainable city of the twenty-first."* He continues by suggesting why this new science is being developed: *"The complex spectrum of humanly modified nature – from the city to its hinterlands – requires the development of a concept of urban ecosystem services that does the following: integrates the built environment* 60*, regards urban ecosystems as novel ecosystems for an ecology of the city* 61 *(Grimm make a distinction between ecology of the city and ecology in the city),* 62 *and understands the political and economic ramifications of these flows."* 63 This new science is being developed to rethink cities as *"already existing socio/natural hybrids with the built infrastructure being part of a city's urban ecology, physically embodying the far-flung nature-based supply chains bringing materials into the city."* 64

The urban ecology as a key sub-element of urban sustainability is still a relatively young and debated concept. It relates to an intrinsic human activity: the transformation of the environment most, notably the creation of cities. Yet, within this discourse a key component is underrepresented, namely space. The spatial dimension is considered a 'given', such as the temporal dimension necessary to understand complex spatial temporal dynamics under which urbanisation takes place. Cities require supporting hinterlands, sustainable urban development needs to find a balance between urban and supporting and remote areas. This is illustrated by Ellis and Ramankutty in their study of anthropogenic biomes of

56 Morton, *Ecology without Nature*; Morton, *Dark Ecology*.
57 McDonnell, "*Journal of Urban Ecology*."
58 Wu, "Urban Ecology and Sustainability."
59 Pickett et al., "Ecological Science and Transformation to the Sustainable City," 10.
60 Moffatt and Kohler, "Conceptualizing the Built Environment as a Social–Ecological System."
61 Francis, Lorimer, and Raco, "Urban Ecosystems as 'Natural' Homes for Biogeographical Boundary Crossings."
62 Grimm et al., "Global Change and the Ecology of Cities."
63 Pincetl, "Nature, Urban Development and Sustainability – What New Elements Are Needed for a More Comprehensive Understanding?," 2.
64 Pincetl, 5.

the world: *"More than 75% of Earth's ice-free land showed evidence of alteration as a result of human residence and land use, with less than a quarter remaining as wildlands, supporting just 11% of terrestrial net primary production."* 65 Yet, the quality of the space, its mode of production and its manifestation as spatial diversity have not yet been covered by the discourse. Considering the high environmental toll global urbanisation as epicentre of human activity and generator of green house gases is already taking on global support systems it is urgently necessary to reconsider the concept of urban sustainability and to critically question the forms and speeds of current urbanisation.

Urban sustainability: A widely accepted definition of urban sustainability identifes social, economic, ecological and political dimensions as contributing to a lasting and resourceful urban development. This very open definition contains underlying ambiguities that need to be resolved. The definition of urban sustainability all too often still depends on the perspective its proponents develop towards it. Allen argues that: *"the apparent consensus on the urgent need to promote sustainable cities has been underlined by significant differences with regards to the questions of what urban sustainability means, why and how to promote it, and for whose benefit."* 66

This struggle is evident in the challenges faced by the UN HABITAT not just to define a common understanding of sustainability in general but also to define a programme for urban sustainability in particular. Since the 1990s the urgency grew to transform the open concept of sustainability into tangible development indices and targets as attempted by the Cities Conference or Habitat II in Istanbul in 1996 and in the wake of the Habitat III conference in Quito in 2016. 67 Examples include the Millennium Ecosystem Assessment, 68 or the Earthscan by the United Nations Human Settlements Programme in 2006. 69 The UN efforts reflect the discourse and the contradictions of the current understanding of urban sustainability: The economic dimension is reflected in *"There is no Sustainable development without Sustainable*

65 Ellis and Ramankutty, "Putting People in the Map," 439.
66 Allen, "Sustainable Cities or Sustainable Urbanisation?," 1.
67 UN HABITAT, "New Urban Agenda."
68 Millennium Ecosystem Assessment (Program), *Ecosystems and Human Well-Being*.
69 Tacoli and Earthscan, *The Earthscan Reader in Rural-Urban Linkages*; Bell and Morse, *Sustainability Indicators, Measuring the Immeasurable? – Gauging Progress in Sustainable Urban Development*.

Urbanization", [70] the social justice idea in 'Harmonious Cities', [71] Global urban trends and threats are identified in 'Urban Sprawl', [72] ecological dimensions are included in 'Cities and Climate Change'. [73] How these conflicting targets are to be reached remains a mystery despite calls for action in 'Planning Sustainable Cities: Practices and Perspectives'. [74]

Returning to the conflicting perspectives on urban sustainability, the ecological and social 'league' argues that *"The sustainable city is one that reduces its reliance on inputs from far-flung places, reduces waste streams, and achieves a measure of social equity."* [75] Wachsmuth reasons that environmental friendliness is missing crucial social and global dimensions of the discussion: *"Expanding the frontiers of urban sustainability social equity and global impacts are missing from measures of cities' environmental friendliness."* [76]

The economic and pragmatic 'league' argues that ecological advance can fuel an alternative economy and can be handled locally. There are two aspects that deserve critique in this model: The advancement of economy through ecology and the aspect of scale or system boundary. Urban sustainability discussion easily falls into the trap of confining the sustainability observation frame to its perceived boundaries: *"Discussions of the environmental sustainability of cities have brought attention to the role of cities within broader forms of regional and global sustainability. Cities are vast consumers of environmental resources and enormous producers of pollution. The point is that the resources which cities consume and the pollution they produce are neither sourced, nor wholly contained, within the territorial boundaries of the city. The ecological footprints of cities now reach around the world, from Antarctica to the Sahara, and from coral reefs to the ozone layer."* [77] Wachsmuth argues that *"Only by expanding the spatial and social dimensions of urban*

70 UN HABITAT, "Land for Sustainable Urbanization 'There Is No Sustainable Development without Sustainable Urbanization.'"
71 UN HABITAT, "State of the World's Cities 2008/2009 – Harmonious Cities."
72 UN HABITAT, "Urban Trends: Urban Sprawl Now a Global Problem."
73 UN HABITAT, *Cities and Climate Change*.
74 UN HABITAT, "Planning Sustainable Cities: Practices and Perspectives."
75 Pincetl, "Nature, Urban Development and Sustainability – What New Elements Are Needed for a More Comprehensive Understanding?," 4.
76 Wachsmuth, Cohen, and Angelo, "Expand the Frontiers of Urban Sustainability," 391.
77 Whitehead, "Sustainability, Urban," 111.

policymaking can it be made truly sustainable and equitable." 78 The economic dimension is often called 'sustainable development' and proposed for the gradual development of cities *towards* ecological and social goals. The understanding of urban sustainability derives from the concept of ecological sustainability in the sense of eco-efficiency in the use of scarce resources. This concept acknowledges the primacy of the economic development as eco-efficiency or 'sustainable development'. 79 This league advocates that a partial solution which prioritises economic aspects is better than no solution. This point of view obscures the fact that the economic optimisation often represses other alternative forms of development. Mössner further argues that *"Developing, promoting, exporting and implementing models of urban sustainability must be understood as a process of gaining political power to decide, to exclude, to construct hegemonies, and to create and maintain social inequalities"* 80. The conflict between economic and social aspects is evident: *"The discourse of sustainable development often is deployed simply to further the interests of the entrepreneurial supportive state and its institutions".* 81 *"Sustainability's radicalism is subverted, as it has been hegemonised by the narrower concept of 'sustainable development'".* 82 The author discussed it as political instrumentalisation in the Gulf State based on the works of Gunder, Davidson, Brown and Mössner: 83

"Gunder traces how planners gradually adopted sustainability as an *'organizing principle of one of the discipline's most important new discursive fields".* 84 This process replaced former concerns about social justice, and environment and emancipation as leading discourses. The uncritical and widespread adoption of sustainability created a *"potentially pernicious interpretation of sustainable development, an often dominant or hegemonic take on sustainability, and how governments have used this interpretation to justify policies that are not necessarily sustainable or even socially just."* 85

78 Wachsmuth, Cohen, and Angelo, "Expand the Frontiers of Urban Sustainability," 393.
79 Cummings and von Richthofen, "Urban Sustainability as a Political Instrument in the Gulf Region Exemplified at Projects in Abu Dhabi.," 257.
80 Mössner, "Sustainable Urban Development as Consensual Practice," 973.
81 Gunder, "Sustainability," 209.
82 Brown, "Sustainability as Empty Signifier," 116.
83 Gunder, "Sustainability"; Davidson, "Sustainability as Ideological Praxis"; Brown, "Sustainability as Empty Signifier"; Mössner, "Sustainable Urban Development as Consensual Practice."
84 Gunder, "Sustainability," 206.
85 Gunder, 206.

He further argues that *"the definition of sustainability can be and often has been deployed selectively by planners or politicians as a materialization of dominant institutional ideologies supportive of growth and capital accumulation that maintains the existing status quo of class inequalities, with limited regard to the environment."* [86] Regarding the Brundtland report and subsequent interpretations of sustainable development, Gunder argues that *"diverse socio-economic and environmental issues are constituted under one mantle of a triple (economic, environmental, equity) or quadruple (plus creativity) bottom line of accounting constituting an all-embracing, sustainable-development rubric."* [87] As we will see, the 'sustainable-development rubric' is unilaterally mobilised in the Gulf by the ruling elites to sustain the status quo." [88]

The concept of sustainable development is ultimately a conservative model. It aims to stabilise a steady state. This is contrary to the idea of *urban development* as a process of transformation from one state into a new one. Transformation may be necessary and desirable in particular considering changing demographics and advancing technologies. The definition of urban sustainability remains vague despite the realisation that all aspects of related social, ecological and economic aspects materialise in space, but little consideration about this space has yet been given yet. We therefore need to discuss the aspect of space for urbanisation as a resource and dimension of urban sustainability in detail.

<u>Space as non-renewable resource</u>: Due to its status as a finite, non-renewable resource space deserves particular attention in the sustainable urbanisation context. Space, considered as mere physical quantity, is not per se sustainable or not. It cannot be 'depleted' by physical transformation, but it can be significantly altered. Alteration makes space unaccessible for other uses and therefore removes it from contributing positively to a habitat. In other words, the use of space determines its resource status as being closer to finite or renewable or both.

In essence, only renewable resources of energy, material and space can be considered truly sustainable as they can be replenished. Non-renewable resources undergo physical transformation that renders their re-use difficult and energy intensive, even if these

86 Gunder, 209.
87 Gunder, 209.
88 Cummings and von Richthofen, "Urban Sustainability as a Political Instrument in the Gulf Region Exemplified at Projects in Abu Dhabi.," 255.

processes of recycling can be managed efficiently. Sustainability envisions the re-use and non-disposal of already accumulated renewable and non-renewable resources. Non-renewable resources have already accumulated in cities, a re-use and re-cycling of these materials would reduce the exploitation of further non-renewable resources and eliminate or delay their waste. Energy and materials can be truly sustainable if deriving from renewable resources. Energy is subject to the laws of thermodynamics (entropy) and cannot be re-used without loss. Concentrated forms of energy necessary for production and transportation will always require a new energetic input. The energetic use can be measured in terms of energetic efficiency.

Space, on the contrary, can only be considered a renewable resource if the space undergoes phases of use and regeneration, such as fallow lands in agriculture or in natural, cyclical changes of space in nature. Urban sustainability necessarily includes a spatial dimension, as urban phenomena inevitably require space to materialise, each element of an urban area such as housing, commerce, infrastructure, agriculture, transport, leisure, etc. requires space. Unlike the example of the fallow land in agriculture, modern urban land use transformation is in the most cases non-cyclical and non-reversible. Built-up land will not be returned to agricultural or natural land unless significant efforts are made or the spaces are left abandoned for a long time. Even in this case the process of urbanisation will have left irreversible marks on the landscape. Similarly, land-production – while technically feasible in the form of land reclamation or land transformation from previously non-suitable surfaces such as water, mountains, underground, aerial or previously untouched ecosystems such as forests or deserts – is an illusion as these processes take a high ecological and economic toll on the regions and hinterlands that support these reclaimed areas. [89]

Under the premise of land being a finite resource – as the surface of the globe is indeed finite – the spatial dimension of urban sustainability poses a conceptual problem as space for urbanisation has to be considered a non-renewable resource. Its use can not be offset by the physical production of space as would be possible with renewable resources. Based on the examples of post-war West Berlin and Inner London Carlow argues that the finite aspect of urban space is a resource that needs to be understood and

89 Wackernagel and Rees, “What Is an Ecological Footprint?,” 125.

managed well. [90] Therefore the concept of efficient use of already mobilised spatial resources in form of present urbanised areas is imperative. Yet, space available for urbanisation is usually much more constrained, this is evident in small countries like Singapore where spatial urban development is limited (at least in the horizontal plane) by the surface area of the small island state. But even there the surface available for urbanisation is much less than the total spatial extent of an administrative boundary. A critique of equating administrative boundaries of cities to their spatial extent and thereby missing the spatial phenomena of urbanisation has been promoted by the discourse on extended urbanisation. [91]

This thesis uses the idea that costs of access and maintenance determine and limit the area available for urbanisation. This conceptual problem can be illustrated by the search for 'peak oil' and its changing forecasts. Conceptually, all oil resources on the planet are finite, but not all oil resources are known and technology to extract them is evolving. Both aspects (new discoveries and advancing, cheaper technologies) will change the potential extract, a demand and a supply side will dictate the speed of extraction and thus determine the peak after which oil production declines – unless new discoveries, technology and the market spin the production to a next level. [92] While the concept has been criticised many times for its imprecise predictions the underlying model is helpful when assessing finite resources. [93] As in Hubbert's model for classifying oil reserves by their state of discovery and technical accessibility one can classify different types of space: the non-suitable, the theoretically suitable, the actually suitable space and the space affordable to mobilise. Unlike in the oil-example the resource 'suitable land for urbanisation' can be determined through remote sensing and does not change. Several geographic, climatic and hydrological factors constrain the theoretically suitable space in Oman. The concept has been applied to the case of Muscat Capital Area and the finite resource space. [94]

90 Carlow, *Limits Space as Resource*, 10.
91 Brenner and Schmid, "The 'Urban Age' in Question," 732.
92 Hubbert, "Energy from Fossil Fuels," 103.
93 Jones and Willms, "A Critique of Hubbert's Model for Peak Oil," 261.
94 von Richthofen and Langer, "Evaluating the Urban Development and Determining 'peak-Space' of Muscat Capital Area.," 8.

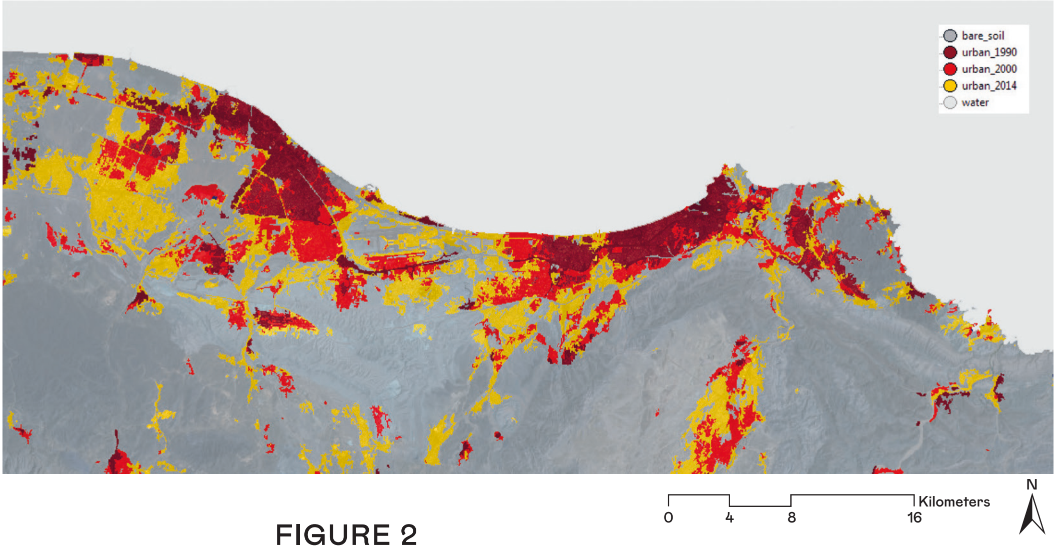


FIGURE 2
Development of built-up spaces in Muscat Capital Area 1984–2014.

The determination of urbanisable areas within a larger geographic region is complex. Recent literature suggests applying power laws of physics and complexity science to urban systems. Findings state that the costs for urban development increase exponentially in relation to urban size as exemplified by urban sprawl. [95] Such costs are not only the sum of materials required to construct the built environment but also relate to all supportive elements of urbanisation such as the provision of infrastructure, connection of larger territories, transformation of landscapes, or transportation of materials and energy. In return, the costs of mobilisation of future urban space is constrained by a dynamic equilibrium. This dynamic relationship represents the actually suitable space for urban development as a cost-space constant. Finally, socio-economic and ecological considerations need also to be applied to determine the affordable space, too.

To summarise, urban sustainability discourses largely ignore the spatial component in their debate about social, ecological, political and economic prevalences, yet urbanisation takes place in space. Physical space per se is not a renewable resource (its physical extent on the globe is finite). With regards to sustainability it is fundamentally different from materials and energy. Due to its physical finality the extent of space is already known. The

95 Bettencourt et al., "Growth, Innovation, Scaling, and the Pace of Life in Cities"; Bettencourt and West, "A Unified Theory of Urban Living"; Bettencourt, "The Origins of Scaling in Cities"; West, *Scale*.

production and use of space determines its qualities and change space into a socially, ecologically, economically and politically renewable resource (the use of common spaces for instance is a renewable spatial resource that can be managed and used over and over again). Dynamic land use transformation can be modelled in analogy to Hubbert's model of peak-oil and classify space by its cost of mobilisation. These costs are not perceived as high for the moment as most externalities such as social and ecological injustice and spatial disparity are not factored into the real estate market. Considering a near future scenario with depleted fossil fuels, the costs for urbanisation and with it the spatial resources that can be activated and managed need to be reconsidered carefully. Instead of accounting only physical space as a dimension of urban sustainability this thesis proposes to investigate *spatial diversity* to describe the transformation process inscribed into space and its future development potential.

SPATIAL DIVERSITY

Spatial diversity is proposed as a new dimension that derives from Lefebvre's production of space, acknowledges the scalar spatial aspects of extended urbanisation, is an expression of urban metabolism and a necessary addition to the concepts of urban sustainability. Spatial diversity is an extension of Lefebvre's concept of difference as an essential feature of urban society. In Lefebvre's terms the more 'different' social space is, the more successful a society has fought capitalist homogenisation. 96 The proposed concept of spatial diversity draws from the concept of biodiversity. We will list key aspects, analogies and methods of inquiry of biodiversity that offer entrance points towards a concept of spatial diversity.

The concept of biological diversity was discussed since Darwin's evolutionary theory, but the term 'biodiversity' was coined by Dasmann only in 1971. 97 Biologists most often define biodiversity as a measure to qualify the diversity of life across all scales and spatial extents as the *"totality of genes, species and ecosystems of a region."* 98 Next to this general scalar and spatial definition biodiversity can also be described structurally as: *"The genetic, taxonomic, and functional variety of all forms of life on Earth, encompassing the interactions among them and the processes that*

96 Lefebvre, *The Urban Revolution*.
97 Dasmann, *A Different Kind of Country*; Benton, "*Origins of Biodiversity*."
98 Larsson, *Biodiversity Evaluation Tools for European Forests*, 178.

maintain them.” [99] On the macroscopic end of the spectrum biodiversity extends systematically to pattern or morphological diversity of ecosystems: *“The variability among living organisms from all sources, including, ‘inter alia’, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part: this includes diversity within species, between species and of ecosystems”.* [100]

Dimensions of biodiversity: The concept of biodiversity thus offers four dimensions on which to engage the constant evolution and transformation of biological systems. *“At the level of landscapes, marinescapes, or ecosystems, biodiversity is conceived on a landscape or larger scale, often in terms of the number, relative frequency, and spatial arrangement of distinguishable ecosystem types, or ecoregions.”* [101] We can distil the following principles from literature on biodiversity that also applies to spatial diversity:

- scale
- spatial extent
- structure
- system

As described in the sections above these four dimensions also apply to space. While Lefebvre’s concept of the production of space is bound in the relation of system (mode of production) and structure (mode of production), the discourse on extended urbanisation is located at the intersection of spatial extent and structure (the ‘territory’), urban metabolism and urban sustainability-related system (the metabolic rates), structure (the directions of stocks and flows) and scale (the observation perimeter). Biodiversity also offers a rich pool of concepts derived from natural observation that help to develop spatial diversity. Amongst those the following are particularly interesting: [102]

- Phylogeny – The evolutionary history of a species or other taxonomic group,
- Dynamics – The changes through time in the size of a population, or in a related measure such as density, and
- Index – The mathematical expression of species richness and distribution as a measure of diversity.

99 Levin, *The Princeton Guide to Ecology*, 777
100 Hawksworth, *Biodiversity*, 6.
101 Colwell, “Biodiversity,” 258.
102 Levin, 779.

Phylogeny: The study of diversification modes through time is a wide field that increasingly uses big data in notoriously data-poor or heterogenous data settings (fossils): *"New phylogenetic comparative methods are now allowing some powerful analytical and meta-analytical studies of large-scale processes of macroevolution. Laws may not exist in biology, but there are generalities or rules, and these can be informative for determining our place on Earth, the future of biodiversity, and conservation policy planning."* [103] Similar problems of data heterogeneity and data coarseness are faced by urban geographers and designers once they venture out of the comfort zone of cadastral urban data. The spatial evolution in time is also challenging given heterogeneous, analogue historical records. Gatti and co-authors propose the idea that biodiversity is autocatalytic in the sense that the species themselves are capable of creating their evolutionary niche as *"a self-sustaining network of mutually "catalytic" entities"* [104] On a larger scale phylogeny allows to distinguish anthropogenic biomes – various generalized regional or global community types – of the world. [105] Phylogeny allowed to establish two rules that can be observed across all biological systems: The first one is called the 'Law of Constant Extinction' or, on the reverse side, the 'Struggle for Self-Preservation'. The second is the systemic difference in biodiversity evolution of land–sea diversification attributed to different metabolic rates of these environments; and thirdly, the latitudinal diversity gradient also links a shift in metabolic rates with temperature and therefore adaptability to evolve over time.

With respect to space we can see that the use of space, in the sense of Lefebvre's production of space, is defined by a constant struggle for self-preservation or, if seen from an outsider's perspective, space is subject to the 'Law of Constant Extinction'. This competitive mode of production – and evolution – ensures that a given mode of spatial production can 'survive'. This resonates with Lefebvre who sees that competition but also cross-influence and mixture as factors of production of space. As with biodiversity, modes of production of space are under stress since the advent of industrialisation and particular under global capitalism. We can now examine the metabolic rates of urban spatial systems and will see that vernacular, grown spatial structures such as evolved in cultural landscapes display a high degree of metabolic efficiency. In other words, these evolved cultural landscapes share spatial

103 Benton, "Origins of Biodiversity," 5–6.
104 Gatti, Hordijk, and Kauffman, "Biodiversity Is Autocatalytic," 70.
105 Ellis and Ramankutty, "Putting People in the Map."

resources, re-use and recycle material and energy, while modern planned urban landscapes often lack these qualities.

Phylogeny also leads to a wide array of ecosystem services as a consequence of biodiversity. The services to quantify depend on the scale of the ecosystem observed, and all scales are interdependent. The argument that ecosystem services providing 'outside' urban areas can offset or mitigate the lack thereof within urban areas has been disproven with the extended urbanisation concept as the dimension of urbanisation is planetary. With regards to urbanised areas a wide range of ecosystems can be identified *"air filtration, micro climate regulation, noise reduction, rainwater drainage, sewage treatment, and recreational and cultural values. It is concluded that the locally generated ecosystem services have a substantial impact on the quality of life in urban areas and should be addressed in land use planning."* 106 ecosystems can be managed and designed to maximise their service benefits: *"ecosystem management consists of all human activities aiming at maintaining ecosystem structures and processes within a domain of development or at bringing them on a path of development, [...] tailored to the needs of present and future generations."* 107 Since ecosystem services are not limited to biological systems, but include inert material and energetic components such as water, energy, material and space, spatial diversity likewise supports and enhances ecosystem services through: *"A set of interacting species and their local, non-biological environment functioning together to sustain life".* 108

Dynamics: Mutual links between biodiversity and spatial diversity directly relate to resilience. Resilience is defined as the capacity to cope with unexpected change without foreclosing future development options. Diversity in multiple dimensions plays a key role in potential of resilience: *"When massive transformation is inevitable, resilient systems contain the components needed for renewal and reorganisation. In other words, they can cope, adapt, or reorganize without sacrificing the provision of ecosystem services. Resilience is often associated with diversity – of species, of human opportunity, and of economic options – that maintains and encourages both*

106 Bolund and Hunhammar, "Ecosystem Services in Urban Areas," 293.
107 Heinimann, "A Concept in Adaptive Ecosystem Management – An Engineering Perspective," 851.
108 Moll and Petit, "The Urban Ecosystem: Putting Nature Back in the Picture.," 8.

adaptation and learning." 109 Folke gives a definition of social-ecological systems that can be transposed for the concept of spatial diversity. Moreover, these systems exhibit 'regime shifts' if stressed too much and not given enough capacity to react: *"Social-ecological systems are constantly changing. Usually one assumes that ecosystems respond to gradual change in a smooth way, but sometimes there are drastic shifts. Regime shifts are known for many ecosystems and these shifts can be difficult, expensive, or sometimes impossible to reverse."* 110 The same dynamics can be witnessed for the spatial distribution of biodiversity across ecosystems: *"The biosphere is not organized as a set of smooth continua in space but rather as a complex 'biotic mosaic' of variably discontinuous assemblages of species. On land, the discontinuities are driven in the shorter term by topography, soils, hydrology, recent disturbance history, dispersal limitation, species interactions, and human land use patterns and, in the longer term and at greater spatial scales by climate and Earth history."* 111

There is a growing recognition that spatial patterns are key to ecological resilience in urban ecosystems. 112 So called 'cultural landscapes' form a subset of this discussion. These ecosystems have been influenced and altered by human activity that has left traces of the past and determines their future: *"Landscapes change because they are the expression of the dynamic interaction between natural and cultural forces in the environment. Cultural landscapes are the result of consecutive reorganisation of the land in order to adapt its use and spatial structure better to the changing societal demands".* 113 Spatial patterns encourage economic innovation in cities 114 and improve urban resilience by means of providing spatial redundancies that can be activated in case of unforeseen system changes or shocks. 115 Modern urban planning and urban geography, as in the case of urbanising Oman, has fallen into a trap caused by two fundamental errors that disregards spatial dynamics and change: The implicit assumption that spatial systems respond in a linear and foreseeable fashion and that human, natural and spatial systems can be treated separately. Folke and

109 Folke et al., "Resilience and Sustainable Development: Building Adaptive Capacity in a World of Transformations," 437.
110 Folke et al., 437.
111 Colwell, "Biodiversity," 261.
112 Alberti and Marzluff, "Ecological Resilience in Urban Ecosystems," 248.
113 Antrop, "Why Landscapes of the Past Are Important for the Future," 23.
114 Duranton and Puga, "Nursery Cities," 1460.
115 Suárez et al., "Towards an Urban Resilience Index," 774.

co-authors recommendations for social-ecological systems are applicable to spatial diversity: The support capacity of spatial systems cannot be taken for granted. The erosion of spatial support capacity leads to vulnerability. According to Folke resilience thinking can help to derive two strategies: Structured scenarios and active adaptive management of space. 116 These are also applicable to spatial diversity.

Index: Diversity can be characterised as *"the condition of having or being composed of differing elements."* 117 Precisely quantifying these elements is a key method of biodiversity studies. Colwell describes concepts, patterns and measurement of biodiversity. The simplest measure is to evaluate the richness of different species in an ecosystem. This absolute amount does not consider the relative proportional composition nor their spatial distributions. Diversity considers both absolute and relative components. 118 A mathematical solution to determine the diversity of a set is Shannon's diversity index for any given set. The Shannon diversity index is thus a measure for spatial diversity as well.

Considering spatial diversity as a 'social-ecological' entity – just as biodiversity – allows us to apply the same concepts to it. Spatial diversification by human modes of spatial production is a constant driver for the evolution of space. These processes take time and have, until now, largely been ignored by planners or been relegated to the realm of the vernacular. Spatial diversity, just like biodiversity, is a provider of a multiplicity of direct and indirect services. Through the quantification of these services spatial diversity becomes an economic and political argument. Just as biodiversity is considered inherently resilient to unexpected threats, spatial diversity is able to cope with anthropogenic threats such as climate change and resource exploitation. Spatial diversity and its inherent informality allow for social appropriation and participation – antidotes to nepotism and corruption that plague development and planning in Oman and elsewhere. Spatial diversity is local and cannot be offset by biodiversity and spatial diversity are intrinsically linked and mutually reinforce each other. Finally, strategies for measuring, managing and preserving biodiversity have been established that can be translated to spatial diversity. ●

116 Folke et al., "Resilience and Sustainable Development: Building Adaptive Capacity in a World of Transformations," 4.
117 "Merriam Webster."
118 Colwell, "Biodiversity," 257–263.

PART

II

THREATENED SPATIAL DIVERSITY IN OMAN

PART 2: THREATENED SPATIAL DIVERSITY IN OMAN

The spatial organisation of Oman is rapidly changing. Urbanisation and infrastructure development increasingly encroach onto gravel deserts, cut across mountains, snake through dry river beds, destroy fragile ecosystems and threaten the scarce agricultural land. 119 When approaching Oman by plane, Muscat Capital Area resembles an endless carpet of single villas built on dusty plots served by endless roads simmering under the Arabian sun. This urban sprawl stretches along the coastline North towards the boarder of the United Arab Emirates. This new territorial organisation has very little in common with the former fluid spatial organisation of space surrounding a network of nuclear settlements and semi-nomadic use of space. 120 Yet this process is very different from urbanisation in other parts of the world and has been widely overlooked in the past or, even worse, been mistaken for 'inevitable' urban sprawl. The relatively large size of Oman, the comparatively small population that lives on it, and the desert landscape are just a few factors that make scientist, politicians and citizens believe that Oman has enough spatial reserves to grow and that changing land use is not dramatic. This dissertation argues that this is not the case. A first approach to identify and recognise spatial diversity was undertaken in a photographic essay documenting the changing land use in Oman conducted in 2014 (SEE FIGURES 3–11). The following images were taken during field work in Oman and selected to exemplify a transect of land use transformation from barren, uninhabited land towards urban conditions in Muscat Capital Area. These images represent conditions that can be found anywhere in Oman.

119 von Richthofen, "Vanishing Omani Landscapes."
120 von Richthofen, "A Critical Reconstruction of Modern Urban Settlement Patterns in Muscat and Al Bāţinah Based on Military Maps," 88.

FIGURE 3
Photo of levelled land and excavations for future residential neighbourhoods.

The process of transformation is subtle but consistent. It starts with levelling land, alteration of topography and removal of obstacles. Hills and mountains are a source of destruction in Oman, since the little amount of vegetation cannot hold back rock-slides. Dry river beds can unleash tremendous forces as occasional rains transform them into torrents of mud and rocks. The modification of surface topography disturbs fragile ecosystems and changes the underground hydrology.

FIGURE 4
Photo of power lines and villas under construction in the outskirts of Muscat Capital Area.

The demographic pressure and a particular land allocation lottery (see below) lead to the proliferation of individual villas across Oman. A power line and a road lay the foundation for a settlement with modern amenities such as TV and AC. Fresh water is trucked in. Given the decentralisation of water and energy, any point in Oman can potentially be urbanised.

FIGURE 5
Photo of Villas in the landscape.

The villas are built on plots devised by the government and allocated by lottery to each Omani citizen, male and female, by the age of 23. Each citizen is entitled to a plot of 30×20 m = 600 m^2 of land regardless of actual spatial need. The Omani government has distributed an estimated 180.000 hectares of land since 1970 without land taxation or a proper land management system. The lottery that was intended as a welfare and prosperity mechanism lead to land-speculation and underdevelopment of large areas due to lack of regulation. [121]

121 Heim et al., "On the Process and Economics of Land Settlement in Oman: Mathematical Modeling and Reasoning in Urban Planning and Design."

FIGURE 6
Photo of the extended urban landscape of Muscat Capital Area that exemplifies the land transformation process.

The houses are built by foreign workers with low skills and are of poor materials. The design is inspired by Indian architecture imported by Indian contractors that coordinate most housing projects in direct commissions for their clients. A nominal stamping fee is collected for each design that follows minimal local planning guidelines. Neither the villa typology, nor the material use is adapted to the climate and stands in stark contrast to vernacular architecture and village typologies.

FIGURE 7
Photo of new neighbourhood showing the limits of the land allocation systems and low urban design guidelines.

Many recipients of the land allocated under this lottery and other private developers aim to maximise the possible land use, regardless of actual need. Often plots are overbuilt with houses and annex apartments, shops and residential flats as long as the building envelope follows the few urban design guidelines; a minimum setback and a maximum height depending on the land use. The lack of urban form accounts for exchangebility and redundancy of urban spaces.

FIGURE 8
Photo of Omani agglomeration following the highway.

Since the allocated plots are distributed randomly, many new residents don't have ties to any former village settlements nearby. The in habitants of these new villas work in the commercial districts of Muscat Capital Area and need to commute over long distances. Opportunity costs for travel distances by individual cars form a new economic constraint for land development. Plots adjacent to the highways are better connected and integrated into the larger, car-based network of Muscat Capital Area.

FIGURE 9
Photo of the Al Batinah plain, now part of the fully urbanised Muscat Capital Area.

The logic of ‘endless’ space availability in Oman gradually transforms all regions into levelled, altered, built-up residential spaces. Spatial diversity is relegated to the fringes such as mountains or dunes that have (not yet) been transformed.

FIGURE 10
Photo of massive highways cutting across pre-historic dunes and fragile ecosystems in Bowsher, Muscat Capital Area. Note that the dunes have already been damaged by so called 'dune-bashing' by Sport Utility Vehicles, quads and buggies.

Infrastructure development, roads, power lines, storm water retention dams, desalination plants, electric power plants, etc. are seen as necessary armature of modern life. Their installation destroys precious ecosystems, cultural landscapes and disrupts urban spaces.

FIGURE 11
Photo of commercial developments in Bowsher, Muscat Capital Area.

Development in the urban centres is guided by economic profit. Following the accessibility logic, multi-story buildings occupy strategic positions within the urban network. Malls and other 'anchor' businesses increase their attraction. Accessible only by cars, they create segregated islands within the urban extent.

The following section discusses the specific geographic, climatic, hydrological, ecological urbanisation constraints that limit the further alteration of topography, hydraulic and fragile ecosystems. These constraints show that space suitable for human habitation and agriculture is indeed limited in Oman. We will then discuss historic, socio-cultural, political, economic and planning aspects of urbanisation of Oman's path to modernity to position the country in a transition from spatial diversity to spatial homogeneity that puts the 'Renaissance' model in crisis: Spatial diversity and with it the possibilities for sustainable spatial development are at risk in Oman.

SPECIFIC URBANISATION CONSTRAINTS: GEOGRAPHIC, CLIMATIC, HYDROLOGICAL, ECOLOGICAL

Geography: The geographical parameters of Oman set the stage for human inhabitation, settlement and agriculture. The Sultanate of Oman is located at on the eastern side of the Arabian peninsula and partly considered a semi-arid zone. The country stretches from the Straight of Hormuz in the north to the mountains of Hadhramaut in the south for about 1500 km. It faces the Indian Ocean in the east and the Empty Quarter desert in the west (SEE FIGURE 12).

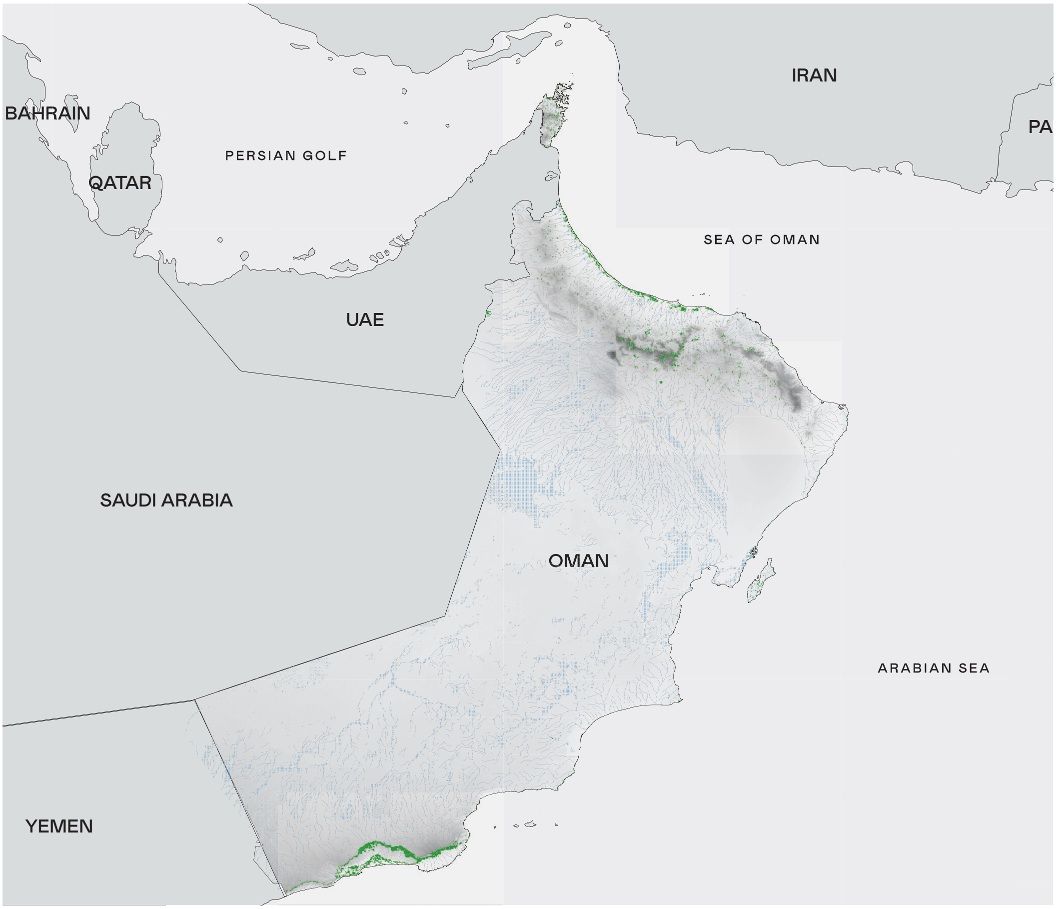


FIGURE 12
Physical Map of Oman and the Eastern Arabian Peninsula.

Geologically, Oman is located at the tectonic intersection of several continental plates. Present Oman was formed by several cycles of "*tectonic uplifting followed by erosion and deposition cycles, with alluvial, terrestrial and raised beach deposits being formed.*" [122] Tectonic movement and erosion formed the spectacular mountain range that parallels the northern coast line peaking at 3028 meters above sea level. The Hajar Mountains form a natural barrier that separates the eastern coastal plain of Batinah with the present Muscat Capital Area from the Omani interior and its oasis towns. These mountains are part of the remarkable geology of Oman that is not only endowed with natural resources such as oil and gas, but also metals, minerals, rare earths and fossil water. The Hajar mountains also block humidity carried by ocean winds from the East and replenish vital aquifers. Oman controls the northern tip of the Arabian Peninsula at the Straight of Hormuz, an important maritime passage point and main exit for Arabian and Persian oil tankers from the Gulf. The central parts of Oman are characterised by various desert landscapes: The dune landscapes of the Empty Quarter and the Wahiba Sands, the gravel and dust deserts and the rock deserts. The southern region of Salalah is set in front of a table mountain that blocks the seasonal monsoon rain and accounts for almost tropical climate. Erosive processes carry rocks, gravel and sand away from the mountains. Alluvial fans characterise both sides, sea in the east and desert in the west, of the mountain ranges. Scholz gives an excellent description of the structural geography of Oman. [123] These geographic features allowed for very scarce and limited human inhabitation in the past, close to the few places with fresh water supply.

The administrative boundaries of modern Oman comprise eleven governorates (muhafazah) that are each subdivided into 61 provinces (wilayat). The Muscat Governorate comprises six provinces – Al Amarat, Bawshar, Muscat, Muttrah, Qurayyat, Al Seeb – but the connected present Muscat Capital Area reaches further into the governorates of South Al Batinah and Ad Dakhiliyah. The administrative subdivision of Oman is a political creation that has little to do with historic and cultural regions. The administrative boundaries were also reorganised and unified in 2011. A historic comparison singling out administrative sub-boundaries will ignore these interconnections. This thesis started out to study urban landscape of Oman. Of course, urbanisation at the northern border of Oman, in particular at the dual cities of Al Buraimi (Oman) and Al Ain (UAE) and at the border of Shinas (Oman) and Hatta and

122 MRMWR, "Water Resources in Oman," 17.
123 Scholz, Sultanate of Oman – Aerial Photo Atlas, 12–18.

Fujeira (UAE) is continuous, yet for the purpose of this study Oman forms a political, economic and cultural entity.

Climate: Oman and Muscat Capital Area are located at 23° North, precisely under the Tropic of Cancer (23° North parallel). This latitude means that the sun is in the zenith at spring and autumn solstices accounting for the world's hottest climate during summer reaching temperatures above 50°C, and making for mild winters. During the summer months from May to October thermal dynamics over the Indian Ocean contribute to a south-western monsoon. The winter season extends from November to April. During this time stable high pressure zones over the Arabian peninsula account for dry weather. Rainfall is rare and occurs only sporadically, leading to flash floods and quick run-offs into the desert or sea. Lasting hot periods can lead to significant droughts. Oman is located next to two main bodies of water that influence its climate and moderate extreme temperatures. The Arabian Sea as side sea of the Indian Ocean brings some water to the eastern coast. This leads to high humidity levels with moist, warm and unstable conditions, in particular for the Al Batinah plan and Muscat Capital Area in the summer months. The seasonal Khareef rain that affects the southern region of Salalah is due to a local form of Monsoon that is powered by Indian Ocean currents. Surface temperature changes in the Indian Ocean are the breeding ground for tropical storms that hit Oman with increasing frequency. The super cyclone storm Gonu caused heavy flooding and destruction in 2007. The Arabian Gulf in the north is relatively shallow and heats up during the summer months. The wider geographic context of landmasses, mountains and water bodies orchestrates the land phase of the hydrological cycle. Airflows are further redirected by the Zagros mountains of South Iran. The Arabian desert is one of the largest in the world. This barren land mass acts opposite to the water bodies. Heat is absorbed during the day and released during the night, accounting for extreme temperature fluctuation and strong winds. These inland winds are blocked by the mountain ranges.

The local climate of Muscat, combining of air temperature, air humidity and wind speed exceeds the thermal comfort zone. Traditional buildings use a variety of passive measures to increase micro-climatic comfort such as self-shading, wind towers and evaporative cooling. The modern settlements rely on air-conditioning. Careless urban design, large road networks, lack of shade, etc. have lead to an intolerable urban heat island effect. The official temperature records 'stop' above 50°C in the shade, but temperatures can reach much higher levels, causing dehydration and death amongst those forced to work outside in particular migrant workers. The temperature gradient falls as one climbs in altitude and the peaks of the Hajar mountain even see occasional snow. Temperature gradients constitute a limiting factor for inhabitable spaces in Oman.

Hydrology and Water: The natural fresh water hydrology of Oman relates to surface water, ground water and springs. It is characterised by natural replenishment through rainfall, condensation of air humidity and pre-historic fossil water resources. The hydrology is directly linked to the geology and geography of Oman.

As is to be expected in a semi-arid climate, the theoretical annual evaporation potential exceeds natural precipitation. It is estimated at "*3.000 mm in the Interior, through 2.100 mm on Al Batinah coast, to some 1.700 mm on the Salalah plain*" while the actual rainfall is much less at only 100 mm. [124] Out of this approximately 5% is redirected into absorbing zones.

In the absence of significant vegetation, the geology determines if water infiltrates into the ground or stays on the surface. Permeable layers such as rocks, gravel and sand will allow water to infiltrate and prevent evaporation into the air. Strata of solid rocks and clay act as impermeable layers. Catchment areas of aquifers range from the coastline to the mountains and can cover vast areas. Dry river beds (wadi) typically carry underground water and swell with flash floods in case of rain. Rainfall is the most significant source of surface water in Oman. It occurs in the mountain areas with up to 350 mm per year and along the coast with up to 100 mm per year. The variability of rain fall is very high. Due to occasional storms many areas of the lower catchments are subject to flood risk. These zones follow the course of the dry rivers and alluvial fans. The flash floods have an important function as replenishers of remote aquifers. Ground water is found below surface sediments and above solid rocks. Some sources of ground water are replenished by rain fall and considered renewable, while others receive little water input and are thus considered non-renewable. The natural national recharge rate is estimated at 1.300 Mm^3/year as a result of indirect infiltration of surface water into the aquifers. [125] Ground water availability differs regionally and is not congruent with the settlement areas. The water deficit is largest in the most populated area of Al Batinah with 47.6% in 2008 and is regarded internationally as extreme water stress. [126] Moreover, the rate of

124 MRMWR, "Water Resources in Oman," 20.
125 MRMWR, 29.
126 MRMWR, 89.

groundwater extraction has in many places in Oman exceeded that of natural replenishment: *"With settlement and development, the demand for water has led to ever increasing interception of groundwater flow by, and abstraction from, dug wells and aflaj. Such interception and use has modified the natural balance; in some areas the rate of abstraction now exceeds the rate of replenishment. In such areas, water levels decline signifying a reduction in the volume of water stored in the aquifer. In some coastal areas, the lowering of water levels has reversed the natural groundwater flow direction with consequent movement of sea water inland."* 127 The non-renewable ground water resources are for the most part unsuitable for direct use in agriculture or human hygiene. Despite strategies to use them to irrigate crops for bio-fuels and indirect filtration or industrial use, they remain a finite resources. The national recharge rate of 1.300 Mm³/year is a direct hydrological constraint and limit to development. The 2008 figure for agricultural use of water of 1.130 Mm³/year almost reaches this level. The 2008 report by the Ministry of Regional Municipalities, & Water Resources states that *"domestic, commercial, municipal and industrial purposes in the Sultanate is estimated at 169 Mm³/yr of which two thirds are derived from groundwater and the balance from the desalination of seawater. It is estimated that three quarters of the present supply return to the hydrological system as wastewater and pipework leakage, although 12 Mm³/year is collected and reused for municipal greening."* 128

Considering a proportional growth of water consumption with increasing population and stable natural water resources Oman is now facing an estimated 320 Mm³/year or a 207 Mm³/year deficit to be covered by desalination (compared to an Omani population of 2.6 million in 2008 and 4.8 million in 2018). The current government water strategy aims to cover up to 330 Mm³/year by 2020 with technical means of aquifer augmentation, desalination and wastewater treatment. This is a long way from the principle that *"Development of the country's water resources should be sustainable in the long-term, not just technically but also economically, environmentally and socially."* 129 Any form of sustainable development needs to reverse this trend and respect this natural recharge rate. The land-based hydrology of Oman in the form of surface water seriously limits the possible area of permanent inhabitation and agriculture in two ways: As limited highly localised resource of fresh-water and as threat of flooding during sporadic flash-floods.

127 MRMWR, 31.
128 MRMWR, 82.
129 MRMWR, 95.

Ecology: The varied topography, climate and hydrology account for a multitude of habitats with numerous endemic species of plants and animals. [130] While the main crop – the date palm – has been imported to the Arabian peninsula and is not endemic, the biodiversity of Oman is its main natural capital. Ecosystem services attributed to this natural capital are directly linked to promotion of biodiversity, water storage, and soil fertility. [131]

The diverse geographic zones of Oman and the extreme climate render permanent and sustainable human habitation very difficult for most parts of the country. The specific geographic, climatic, hydrological and ecological urbanisation constraints limit possible settlement area dramatically. This becomes evident with the following scalar comparison: The surface area of Oman compares to that of Italy, yet the population of Oman does not exceed that of the metropolitan region of Venice. A closer look at the historic settlement distribution as developed in the following chapters reveals that urban development was closely linked to the limited natural hydraulic resources that catered for agriculture and settlement alike.

OMAN'S PATH TO MODERNITY: HISTORIC, SOCIO-CULTURAL, POLITICAL, ECONOMIC ASPECTS OF URBANISATION

History: Oman's past borders were always fluid and do not correspond to the administrative boundaries of modern Oman. Its geolocation poised Oman to engage in sea-trade which dates back to the Bronze Age. [132] Omani culture was enriched by many outside influences bringing back technology for irrigation systems such as falaj from Persia, food staples such as rice from India and the date palm from Iraq. Omanis became colonisers in Baluchistan (current south Iran and Pakistan), Malabar (current India), the Swahili Coast (East Africa) and Zanzibar (current Tanzania), and were in return colonised by the Portuguese in the 16th century and then put under British protectorate in the 19th century. By 1850

130 Pickering and Patzelt, *Field Guide to the Wild Plants of Oman*, 34.
131 Bidak et al., "Goods and Services Provided by Native Plants in Desert Ecosystems," 433.
132 Cleuziou and Tosi, "In the Shadow of the Ancestors. The Prehistoric Foundations of the Early Arabian Civilization in Oman," 138–40.

Oman controlled large parts of the Gulf coast, the eastern Arabian peninsula and eastAfrica. Despite external domination, Oman still fared well in seatrade of spices, wood, slaves, weapons and merchandise, as ships from Europe had to circumvent Africa to reach India and beyond. Large parts of the transport were covered by Omani ships. The opening of the Suez Canal in 1869 cut right through the Omani sea routes and lead to a decline of the Omani colonial power. The self-inflicted isolation of Oman during the first half of the 20th century and the relatively late discovery of oil in 1967 lead to further diminishing international significance and poverty. During this time many Omanis were exiled in other Gulf countries seeking work. The borders of modern Oman were drawn by British administrators mostly in their own geo-political interest, at the time of de-colonialisation and the Cold War. Presently Oman shares borders with the United Arab Emirates, Saudi Arabia and Yemen. Across the Gulf and the Ocean lie Iran, Pakistan and India. These borders are the result of post-colonial independence. Oman was of strategic importance during the World Wars and later during the Cold War of which Soviet invasion maps are a remarkable witness. [133]

Oman's path to modernity was propelled by the ascension to the throne of Sultan Qaboos bin Said Al Said on 23rd July 1970. Sultan Qaboos, by then 30 years of age and educated in the UK, chose to part with the isolationist politics of his father, Sultan Said bin Taimur. Backed by British forces he managed to appease uprisings in Dhofar and unite the country.

Socio-Culture and Religion: Islam arrived in Oman during the 7th century AD. Today, the majority of Omanis are Ibadi muslims with Sunni and Shia minorities, together making up 85.9% of the population, followed by Christians 6.5%, Hindus 5.5% and Buddhists 0.8%. [134] The religious leader of the Omani Ibadis is the Imam, typically from a noble family. The worldly leader is the Sultan, who reigns over Oman in absolute monarchy, typically passed down by inheritance. Since the present sultan has no heir, a future sultan has been appointed from his extended family. It is said that 57 original tribes form the contemporary Omani society. These tribes are each headed by a sheik. Fertility rates were as high as 7.3 children per women in 1970, soaring to 8.3 in 1982, gradually declining

133 Soviet Army, "Muscat, East Batinah Coast"; von Richthofen, "A Critical Reconstruction of Modern Urban Settlement Patterns in Muscat and Al Bāţinah Based on Military Maps," 88.
134 CIA, "Factbook – Oman."

towards 3.0 in 2005 where they stabilise at the moment. 135 The total population of Oman rose from an estimated 750.000 inhabitants in 1970 to 4.5 million in 2016 (the later figure includes expatriates, see figure 13). 136 With a median age of 29 the population is very young, seeking employment and eager to settle down which, according to the 'Renaissance' model, entitles them to build a new home on a vacant plot of land. The all-encompassing care of the State is a guarantee for social stability and for the preservation of the status quo, 137; a concept that the young Omani begin to challenge. 138

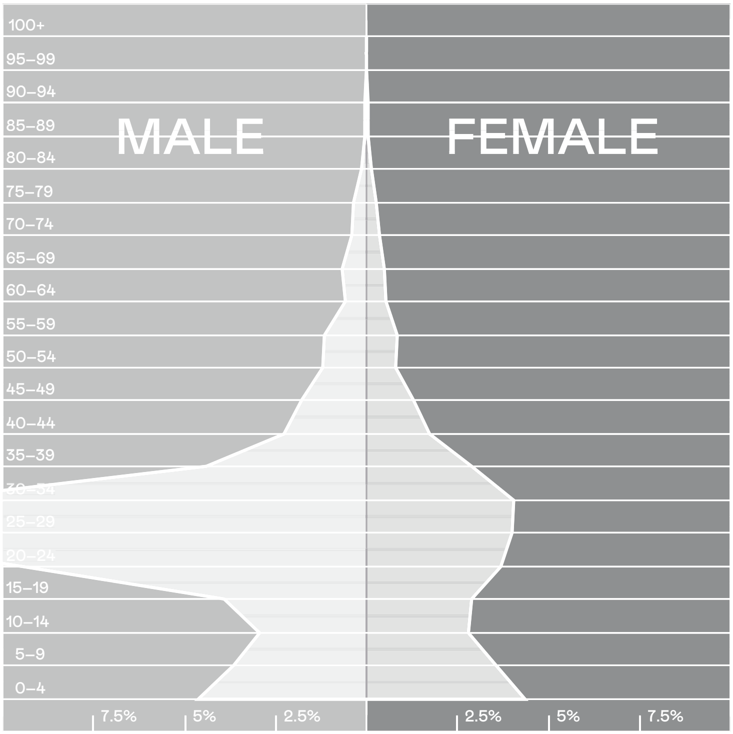


FIGURE 13
Population Pyramid of Oman 2017. The large number of expatriate workers account for the disproportionate male population in the bracket 20–35 years. 139

Modern Oman is a mixture of diverse ethnic groups and cultures. Next to Arab tribes, influences come from neighbouring countries such as Iran, Pakistan and India, but also from former Omani

135 World Bank, "Fertility Rates – Oman."
136 "Population Pyramid of Oman."
137 Oxford Business Group, *The Report*, 2010, 202.
138 Windecker, "Medienbuch Oman."
139 "Population Pyramid of Oman."

colonies along the east African coastline. The nation-making process initiated after 1970 aimed to craft a modern Omani population. It was necessary to overcome tribal competition, and also to integrate the returning Omani diaspora. This phase was named the 'Omani Renaissance' in 1974 by the Sultan and represents the definite vision of growth and development for Oman. Currently, 45% of the population of Oman are expatriates, most of them migrant workers with limited rights and tied to the *kafala* sponsorship system. They work in agriculture, construction or domestic services. It remains a challenge to integrate the foreign immigrants that contribute to the growth of the country's economy but are denied basic rights to travel freely, establish residence and businesses or to vote. International migration has already transformed the region and will continue to transform Oman. This large part of the population, their fluctuation with the prevailing economic situation and their uncertain future add another dimension to the planning challenges of Oman.

Politics: The Sultan of Oman is the absolute monarch, who oversees all aspects of political life in Oman as he is also supreme commander of the armed forces, prime minister and minister of defence, foreign affairs, and finance. [140] Since 1991, the 'Majlis al-Shura' acts as consultative council. It was awarded more powers after the so-called Arab Spring of 2011. In this feudal system, where absolute power lies with Sultan and citizens give up their civil rights, they are in return widely exempt from duties, taxation and other civil responsibilities. Women still face difficulties in this patriarchal society, yet enjoy much larger degrees of freedom than in most neighbouring countries. Media and communication are strictly controlled by the government, but institutions are increasingly being challenged by social media and the diffusion of mobile internet. [141] Yet, Oman still ranks low in the Bertelsmann Political Transformation index at position 114 of 129 globally. [142] It remains an open question whether Oman will make the transition in to a constitutional monarchy with broader human rights in the future.

Oman's international diplomacy is a reflection of past and present ties. It maintains good relationships with both Arab (Sunni) and Persian (Shiite) neighbours and often adopts a neutral role in the Gulf Cooperation Council. It has historic ties to India and East

140 Allen, *Oman*, 56.
141 Windecker, "Medienbuch Oman."
142 Bertelsmann Stiftung, "BTI 2016 – Oman Country Report."

Africa. Oman has excellent relations with all Western powers as well as Israel. Its future in terms of political, economic and spatial development is intrinsically linked to these conditions.

Economy: Until the middle of the 20th century, modern infrastructure in Oman was non-existent, the education system archaic, medical services of a very low standard. Foreign involvement and investment was restricted. The economic upturn and change that triggered and enabled the modern Omani society was closely linked to the discovery of oil in 1962 under then Sultan Taimur. The export of the first barrels occurred on 27th July 1967. A latecomer in comparison to other Gulf states where oil was discovered oil as early as 1927 (Iraq) or 1938 (Saudi Arabia and Kuwait), Oman also produced smaller quantities of crude due to limited natural reserves. Natural gas was exploited since 1978. [143] Due to its geographic location at the eastern tip of the Arabian peninsula it was further impossible to export natural gas without laying pipelines across neighbouring countries to reach markets abroad. Liquefaction plants that were only commissioned in 2000. Yet Oman's oil exports were propelled by the 1973 oil crisis and subsequent price hikes. Since then, a stream of oil fuelled the economic development. This steady source of income lead to a transformation from a pre-modern society based on agriculture, fishing, caravan trade and sailing to a modern wellfare state. Up to the present day, "*Oman is heavily dependent on its dwindling oil resources, which generate 84% of government revenue.*" (SEE FIGURE 14) [144] The vast majority of modern Oman's wealth accumulation including the built infrastructure directly stems from revenues generated by export of fossil carbohydrates. According to a report by the Oxford Business Group in 2014, *"oil and gas revenues account for 90% of government revenues, 52% of GDP and 67% of merchandise exports"*. [145] The oil and gas sector currently only employs 55.000 people currently in Oman, while the sectors that follow agriculture, service industries, tourism and fishing employ the majority of the working population. This means that the Omani economy, government spending and exports would collapse in case the oil and gas sector ebbs down. This single dependency on one revenue stream creates a strong vulnerability for both the economy and society as a whole. The downturn of global economies and the subsequent lower demand for oil saw prices plummet to a third of the their previous levels in the past but also as recently as

143 Petrol Development Oman, "Historical Timeline of Petrol Development Oman (PDO) between 1937 and 2016."
144 "Index Mundi – Oman."
145 Oxford Business Group, *The Report*, 2015.

2015. Oman's GDP dropped in 1985, 1996, 2008, 2014 and 2016 due to adverse global oil prices. 146 Each crisis lead to counter-measures such as a policy in favour of the national workforce called 'Omanisation' in 1988, privatization of the large public sector since the 1990s, membership in the World Trade Organisation (WTO) in 2000, international tourism, the controlled opening of the real estate market to foreign investment, and Public-Private Partnerships. 147 Oman produced about 1/10th of the oil that Saudi Arabia produced in 2017, but has only about 1/50th of the reserves left in comparison. (SEE FIGURE 15) 148 This means that Oman cannot actively steer oil prices by increasing or decreasing production, but must wait until favourable oil prices justify a fuller production again. Its reserves are smaller in quantity and harder to access than those of neighbouring countries. Thus fluctuations in global production and prices hit Oman first as there is very little buffer. Next to the larger environmental question associated with CO^2 emission and global warming, the negative consequences of an oil-dependent economy were recognised in the 1990s, when the first economic diversification plans were established 149 and re-instated with the "Tanfeedh" programme by the Omani government in 2016. Overspending by 133% lead to a 6.5 billion Euro deficit in 2016. Disregarding global oil price decline and finite national resources the freshly released Omani Vision 2040 still counts on oil and gas for 80% of the future revenues. 150 In the absence of a larger public debate about oil-dependency, governmental spending and private sector behaviour continues in a 'business as usual' manner. Oman ranks 5th in the world with a per-capita CO^2 emission of 20t/year, compared to 16t/year in the United States and 8t/year in China in 2016. 151 Oman generates most of its electric energy and desalinates all its water using combustion power plants. In addition, Oman invited energy intensive industries such as aluminium and fertiliser production to produce in Oman using local fossil energy. These export products all depend on fossil resources and have a lasting negative effect on the global climate. Not surprisingly, the local economy also relies heavily on cheap fossil fuels. Land, water and air transport and mobility are based on combustion engines. Even if the resources can be stretched further, they are not renewable, therefore a change in the prevailing development model must occur.

146 World Bank, "Oman | World Development Indicators."
147 Oxford Business Group, *The Report*, 2010.
148 "List of Proven Oil Reserves."
149 Development Council, "FYDP," 1991.
150 "The Sultanate of Oman Is Taking a Kicking – Cheap Oil Makes It Hard to Buy off Dissent."
151 "Oman – CO_2 Emissions per Capita (Metric Tons)."

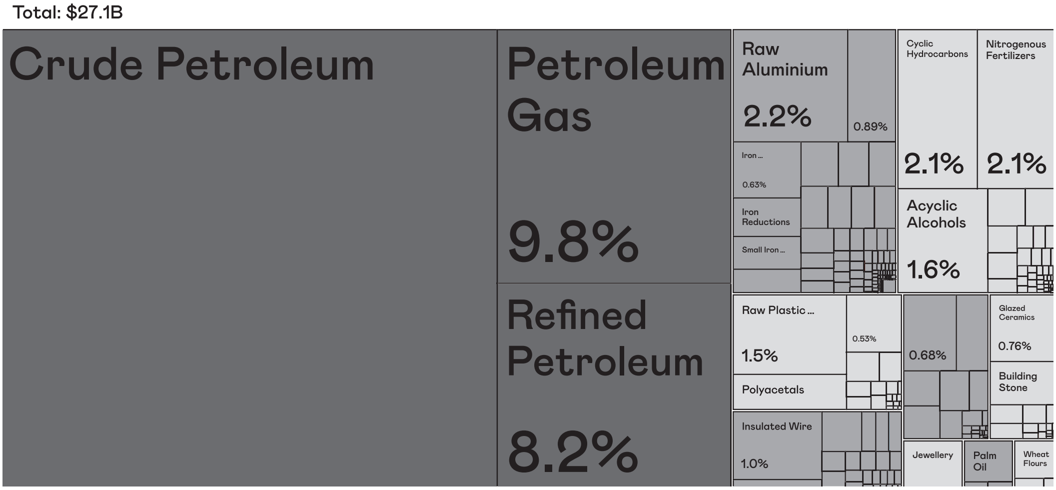


FIGURE 14
Diagram of GDP of Oman.[152]

RANK	COUNTRY	OIL – PROVEN RESERVES (BBL)
1	Venezuela	2,97599000000
2	Saudi Arabia	2,67899000000
3	Canada	1,73100000000
4	Iran	1,54599000000
5	Iraq	1,41399000000
6	Kuwait	1,03999000000
7	United Arab Emirates	97800000000
8	Russia	80000000000
9	Lybia	48009000000
10	Nigeria	37199000000
11	Kazakhstan	30000000000
12	Qatar	25379000000
13	United States	20679000000
14	China	17300000000
15	Brazil	13150000000
16	Algeria	12199000000
17	Angola	10469000000
18	Mexico	10259000000
19	Ecuador	8240000000
20	Azerbaijan	7000000000
21	Oman	5500000000
22	India	5475000000
23	Norway	5366000000
24	Egypt	4400000000

FIGURE 15
Diagram of Proven Oil Reserves. Source: "List of Proven Oil Reserves" 2017.

152 "MIT Media Atlas – Oman."

The socio-demographic and macro-economic changes induced by the 'Renaissance' lead to an unprecedented urban growth visible in an array of urban infrastructures: Housing, schools, shops, mosques, hospitals, police and fire stations dot every last village in Oman. Smaller towns feature secondary education and administrative centres. Larger cities have universities, shopping malls, ministerial and diplomatic districts, palaces, hotels, airports, ports. Agglomerations merge to form a continuous urban carpet. The administrative boundaries of Muscat stretch for more than 100 km, but the built-up urban fabric extends north to the border of the United Arab Emirates, where urbanisation continues in the same way. Co-production desalination, natural gas liquefaction and aluminium-power plants dot the coastline. Oil-fields have their own airports and medical infrastructure. The harbour of Duqm is planned to rival Jebel Ali port of Dubai. All settlements in Oman are reachable by paved road, several thousand kilometres of modern highway cross even the most challenging terrain. Mobile internet reaches the last corner of the desert and the mountains. An international rail network is planned to connect the Gulf state passing by Muscat. Within two generations the whole country has been reconfigured. The specific historical, socio-cultural, political and economic aspects of modern Oman draw a picture of a young and very fragile development. The country absorbed many influences during its history and has a diverse population. De-colonialisation lead to stability and nation building, while the cheap and unrestricted use of fossil resources spurred the economic and demographic development, the 'Omani Renaissance'. This model found a spatial manifestation in the near-total urbanisation of the country. As fossil energy resources diminish, this model will not be economically, socially, environmentally and spatially sustainable any more.

DIVERSE PRE-RENAISSANCE LAND USE STRUCTURES

In search of an alternative spatial development strategy for Oman it is helpful to look at the origins of settlement patterns, their configuration and their dynamic relationship with the land use resources that supported them. While the 1970 'Renaissance' is often used as a marker and starting point of modern development in Oman it did not happen out of nowhere.

Early geographic descriptions of Oman coming from visiting travellers, merchants and administrative agents necessarily contained information about the cities, notable buildings, trade goods and their population. 153 Naval maps of the port and town of Muscat date back to the 17th century. Early photographic views of Muscat exist since 1900 and the first areal photographs were taken in 1938 by the Royal Army (UK). These sources have great historic importance and show that Muscat was a small, densely built, heterogenous and vibrant port town.

A map of pre-1970 settlement patterns of Al Batinah region, roughly comprising the present Muscat Capital Area, based on field work conducted by the author, informs about the original land use structure (SEE FIGURE 16). 154 The map reveals that urbanisation in Oman formed around existing settlements, trade routes and in close proximity to agricultural land. This network of urban clusters and trade connections across the coastal region of Al Batinah prepared the ground for the later urban structure of Muscat Capital Area. Heterogenous settlement structures supported multi-directional urban growth patterns. The pre-modern land use structure directly linked possible spaces for urbanisation to natural hydrologic features and surface structures.

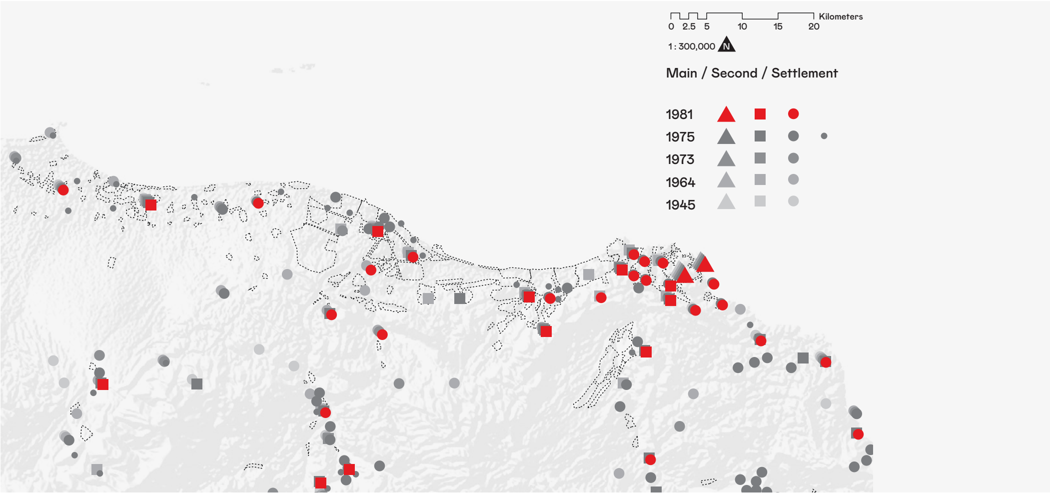


FIGURE 16

Pre-Renaissance Settlement Patterns in Al Batinah ca. 1940–1980. Source (von Richthofen 2017).

153 Bent, *Muscat*; Lorimer, *Gazetteer of the Persian Gulf, Oman and Central Arabia*; Skeet, "Ian Skeet"; Peterson, J.E., *Historical Muscat*; Gaube and Sālimī, *The Ibadis in the Region of the Indian Ocean. Sect. 1.*

154 von Richthofen, "A Critical Reconstruction of Modern Urban Settlement Patterns in Muscat and Al Bāţinah Based on Military Maps," 88.

The maps produced by the author in 2017 contrast with the first systematic study on urbanisation in Oman conducted by the German geographer Fred Scholz who travelled to Oman in the 1970s. Scholz' first research interest were nomads of inner Oman and oasis settlements. 155 Since these places were difficult to access and needed substantial preparation time including waiting for governmental permission, Scholz decided to study the transformation of historic Muscat into a capital city (interview conducted with Scholz in Berlin). 156 He documented as much as possible by note taking, ground survey, airal photography and balloon photography. His observations extended to other historical settlements in Oman. He produced the first modern areal photography atlas in 1978 and geographic introduction to Oman in 1980. 157 Scholz was able to record the built-up environment in plans and maps and added socio-economic studies on commercial activities, clan affiliation, and social status. He was aware that he was documenting a country under rapid change. Demolition works in historic Muscat to clear space for the new palace and administrative buildings started in the 1980s. He also referenced with contemporary geographers' work such as Cordes and Reichert that already recognized the initial challenges to urbanisation faced in Muscat as specific starting points for a unique urban form. 158 Yet, his views on the geography of Oman and the urban structure of Muscat Capital Area were the direct result of coarse and incomplete data availability, limited analogue technology and his Western structuralist pre-conception of society and space. The impression of a blank slate and the complicity with the paradigm of economic growth laid the conceptual ground for the post-1990s urban sprawl.

The estimated number of inhabitants supported in the pre-modern settlement structure as describe by the author in 2017 was limited by the natural conditions and prevailing building, farming and transport technology of the time. These earlier settlement patterns can be seen as steady-state systems of urbanisation based a study of urban metabolism. 159 During a time of relative isolation and

155 Scholz, "Landverteilung Und Oasensterben: Das Beispiel Der Omanischen Küstenebene Al Batinah"; Scholz, "Falaj-Oasen in Sharqiya, Inner-Oman."
156 Scholz, Cartographic methods and archive of my geographic surveys of Oman in the 1980s.
157 Scholz, *Sultanate of Oman – Aerial Photo Atlas; Scholz, Sultanate of Oman – Geographical Introduction.*
158 Cordes, "Öl Macht Städte. Abu Dhabi Town."; Reichert, *Die Verstädterung Der Eastern Province von Saudi Arabien Und Ihre Konsequenzen Für Die Regional- Und Stadtentwicklung.*
159 Baccini, *Metabolism of the Anthroposphere.*

untapped fossil resources early Omani settlements relied purely on solar energy gains that accumulated biomass for food and fuel. The limiting factor in the production of biomass was the availability of fresh water. These urban network structures and agriculture, in particular their supporting irrigation systems, were carefully maintained and show lasting historic continuity. [160]
The pre-modern settlement patterns demonstrate the limit of the natural support capacity in the Batinah region. This capacity has been overly inflated during the 'Renaissance' area of cheap fossil energy. A first step towards sustainable spatial development is to assess this capacity, its extent and structure, and to link it to smart spatial planning, advanced technology and renewable energy.

CHANGING RURAL SYSTEMS

The changing rural systems in Oman have been documented by geographers mostly from the rural perspective before and during the land use transformation process set in by the modernisation. The research falls into two categories: Studies of Omani oases on one hand and the studies of agricultural systems on the other. Contemporary studies on the rural-urban interface are scarce with the exception of Abdelaal's work on the urban sprawl in rural areas, [161] and changing agro-economics in Oman by Zekri. [162]

The 'Khabura Project', a decade-long live study of changing rural systems in Oman, is a comprehensive examination of agricultural space in the country. [163] The project saw several phases and the director, Dutton, stayed in Oman from 1973–1994. It marks the transformation, degradation, disappearance or conversion of traditional agriculture and attached life-styles and settlement patterns in Al Batinah coastal region that is by now agglomerated in the larger Muscat Capital Area (SEE FIGURES 17 AND 18). Dutton starts with the description of the traditional forms of agriculture that were self-sufficient and sustainable: *"Omani villagers [...] retained full responsibility for the management of their rural resources on which they depended for their livelihoods and for life itself, and had evolved effective communal systems for their development and conversation. These were exemplified by regulations governing the*

160 Gangler, "Oasis Settlement Structures/Oman."
161 Abdelaal, "Rural Urban Linkages for a Sustainable Oman: The Case Study of Transformation in Fanja."
162 Zekri, Al-Rawahy, and Naifer, "Economic Impact of Salinity: The Case of Al-Batinah in Oman."
163 Dutton, *Changing Rural Systems in Oman.*

traditional falaj water supply network. People worked interdependently, responding to the contributions made by other members of the rural communities in a system of mutual self-reliance. They also lived in harmony with their environment in a manner which time had proven to be truly sustainable." 164 Dutton then describes the change induced by the oil exports. The economic changes also changed land use patterns, spatial requirements and any obligation to maintain fragile rural systems: *"These changes radically improved family incomes and standards of health and education, and the rural population grew rapidly as did its demand for water and land. People were much less dependent than previously, for life and livelihood, on the proper management of rural resources."* 165

Methodologically, Dutton developed a model of an 'idealized pre-oil rural community' for the village of Araqi based on his observations across the Al Batinah region: *"A principal characteristic of our idealised rural community of Araqi was the interdependence of its inhabitants. [...] Interdependence created a significant degree of effective independence from the world outside. [...] And to the extent that it was truly reliant on its own resources the community knew, that it alone was responsible for the maintenance of the community; responsible economically, socially, materially and spiritually."* 166 As Dutton sums up: *"The idealised community as a whole may be said to have understood the meaning of 'sustainable development' long before the phrase was coined."* 167

164 Dutton, 1.
165 Dutton, 3.
166 Dutton, 8.
167 Dutton, 9.

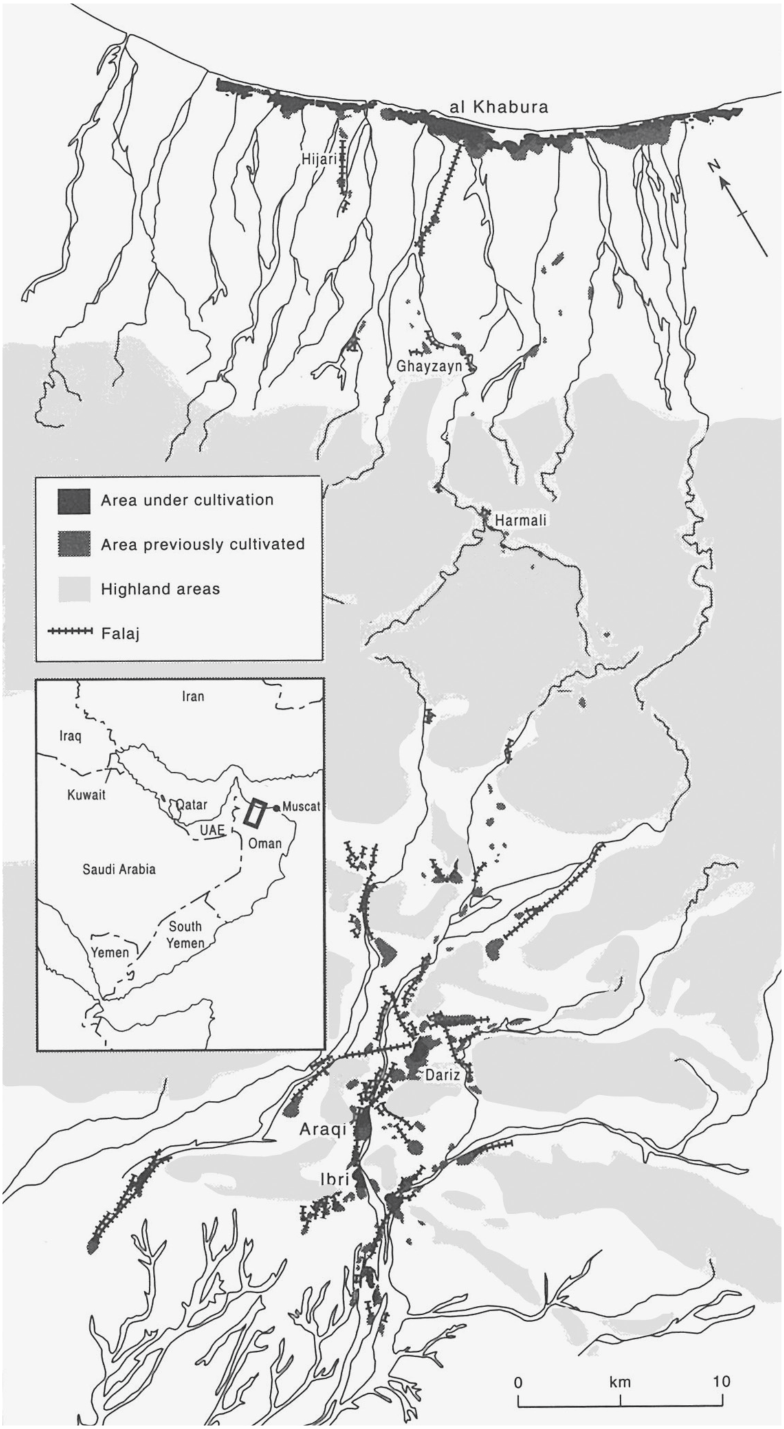


FIGURE 17
Map of the Khabura Project Research Survey – A linked urban landscape stretching from the coast of the Indian Ocean across the Hajar mountains to the Omani interior. Based on (Dutton 1999)

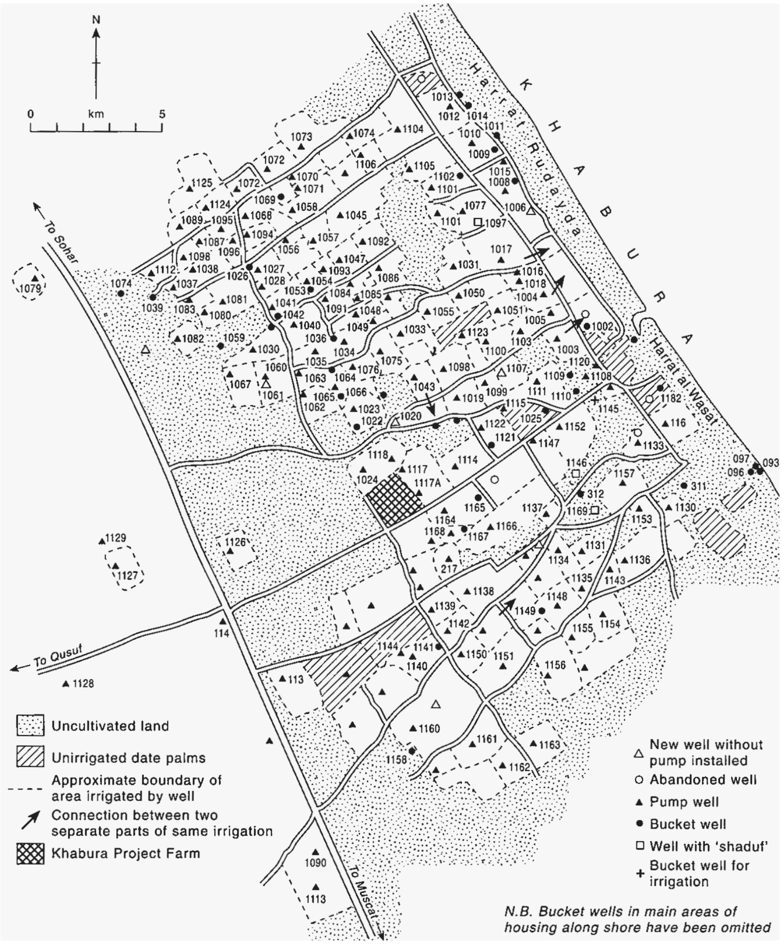


FIGURE 18

Map of the Khabura Project Research Survey – Detailed map of the coastal agricultural settlement system. Based on (Dutton 1999)

This idealization illustrates two points that are crucial for the formulation of a future sustainable urban development and resilience: *“First, the benefits that accrue to the community from interdependence and independence, and second, the vulnerability of the community, and the interdependence and independence of its people, to the forces of rapid regional change induced by oil.”* 168 The water regime structured all activities and enabled a sophisticated interplay of production of agriculture and space: *“Primordial amongst these resources was water, provided for the village as a whole by a single communally owned falaj, a traditional system of raising water for irrigation which had the great virtue of not draining the aquifer. To maintain the falaj for future usage, to work the*

168 Dutton, 9.

discipline of the six day rotation of water [based on a seven day week to give equal access to all community members and respect the religious holiday on the seventh day]*, and to irrigate continuously night and day according to an exact time formula modified to fit different winter and summer requirements demanded a high order of responsive control and interdependence."* 169 *(additions by the author)* Scholz had made similar observations during the study of isolated oasis settlements of inner Oman where agriculture and settlement pattern formed not just a tight union but also showed traits of co-evolution. 170 Dutton explains in detail the various building materials derived from the adaptive re-use of plant fibres: *"One of the main uses of the palm fronds was in the manufacturing of* du'un*, or sheets of* barasti*. The fronds were all cut the same length, partially trimmed of their leaflets, steeped in water to make them pliable, laid side by side and knotted together using local rope to make a 'modular' building sheet measuring about 5m by 2.5m. Such sheets were used to construct houses on the whole length of the Batinah coast where on the shoreline, being sandy, alternative building materials were in short supply."* 171 Wheat was a labour-intensive crop that disappeared in the 1970s under the influx of cheaper Australian wheat imports. The connected system of labour disappeared as well and the distribution of falaj water became irrelevant. (Not like alfalfa that was still sought after as crop for animal fodder). The interdependence of work also demanded a highly diversified labour force. Once this labour became obsolete for economic reasons the whole system collapsed.

Dutton marks the beginning of the end of traditional rural systems with the depletion of aquifers: *"Clues about declining well water levels in the Dhahira during […] up the mid-1970s were obtained by asking farmers about the history of their wells since pump installation. […] Evidence of falling water levels was common. […] The diesel pumps thus posed an important threat to the sustainable use of an essential and scare resource, water."* 172 Until then irrigation pumps were powered by muscle power. Dutton deducted from the disintegration process of the skilled labour force, that: *"wasted local raw material, undermined the position of skilled craftsmen, ended the interdependence of the members of the community and made the community as a whole unnecessarily dependent on the outside world."* 173

169 Dutton, 9.
170 Scholz, "Falaj-Oasen in Sharqiya, Inner-Oman," 64.
171 Dutton, *Changing Rural Systems in Oman*, 26.
172 Dutton, 37.
173 Dutton, 49.

This process finally leading to the near total decline of the traditional agricultural industry: "*The date palm, easily the dominant crop, lost value as a foodstuff and as a source of craft materials. Wheat, an important minor crop in the interior villages, disappeared almost completely from the falaj gardens and could not be replaced. [...] Dried limes produced in the Batinah coast lost their export market in the Gulf. [...] Finally, in agriculture most of the indigenous labour force was replaced by cheap and largely unskilled labour from the Indian sub-continent.*" 174

The oasis settlements of Oman have been the subject of continuous studies. 175 Oman features several types of oasis settlements: The mountain oasis villages capture springs at the source in high altitude. Places such as Balad Seed and Hat in the Hajar mountains divert mountain torrents to irrigate terrace fields. Large quantities of water also surface a the foothills of mountains at the exit of a large catchment area. The town of Nakhl is built around such a low land oasis. Due to the permeability of the top layer, fresh water then runs underground where it can be reached by digging wells or constructing sophisticated underground dams and irrigation channels. According to the Ministry of Regional Municipalities, & Water Resources in Oman, aflaj currently provide 680 Mm^3/year and irrigate 26.500ha of agricultural land. 176 The falaj Daris serves the Nizwa region and is estimated to be 8 km long. The ingenious pre-historic underground aqueduct system of Oman was awarded UNESCO world heritage status in 2006. 177

The topographic conditions of Oman create a complex hydrography that replenishes aquifers, most prominently visible in oasis settlements. Traditionally, irrigation, food production and settlement patterns were interlinked in Oman. Water was captured in various sophisticated ways and lead to areas prone to irrigation. Oasis settlements along the coast differ in hydraulic setup from mountain and hinterland oasis settlements. 178 Scholz recognised the spatial-functional causality of use of water and space by

174 Dutton, 49.
175 Scholz, "Landverteilung Und Oasensterben: Das Beispiel Der Omanischen Küstenebene Al Batinah"; Scholz, "Falaj-Oasen in Sharqiya, Inner-Oman"; Gangler, "Oasis Settlement Structures/Oman"; Korn and et al, "Tiwi, Ash Shab and Wadi Tiwi: The Development of an Oasis on the North-Eastern Coast of Oman"; Dorr and Richardson, *Arts and Crafts of Oman*; Siebert, Nagieb, and Buerkert, "Climate and Irrigation Water Use of a Mountain Oasis in Northern Oman."
176 MRMWR, "Water Resources in Oman."
177 Angelakis, *Underground Aqueducts Handbook*, 497.
178 Scholz, "Falaj-Oasen in Sharqiya, Inner-Oman."

analysing smaller oasis settlements: *"The settlements of Inner Oman are all, without exception, linked to oases. The basis of these are ghayl- or qanat-aflaj.* [179] *Only in the case of a few mountain oases does the water originate from elevated karst sources."* [180] Scholz continues to explain that the social and functional organisation had a direct spatial expression: "*Such means of existence require special organisation and certain spatial patterns of water channel routing and land subdivision. It often results in quite specific forms of internal differentiation and spatial layout of the settlements."* [181] The size of the agricultural land depended directly on the capacity of the hydraulic system 'falaj'. The more water it carried, the larger the irrigated area. The water also followed the topography in a slight downhill direction. Settlement zones emerged immediately adjacent to these irrigated areas on land that was not irrigable. Water was also recycled on the spot. Its use followed a strict social order codified in the arrangement of the built-up environment next to it. The first use was reserved for ritual religious activities, the second use for households activities, the third use for washing and the last use for irrigation at which point all fresh water was absorbed by the agricultural-urban system. Hydraulic system, agricultural land and settlements were interrelated and interdependent forming a nexus. Harnessing water for irrigation meant carving out inhabitable space from the otherwise uninhabitable desert (SEE FIGURE 19).

179 Wilkinson, *Water and Tribal Settlement in South-East Arabia.*
180 Scholz, "Falaj-Oasen in Sharqiya, Inner-Oman," 275.
181 Scholz, *Muscat – Then and Now Geographical Sketch of a Unique Arab Town*, 399.

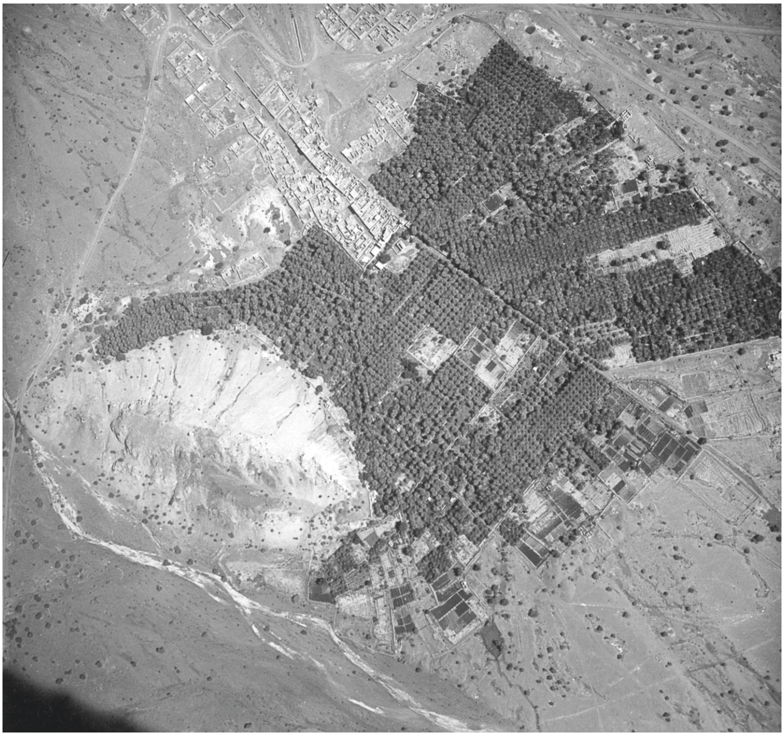


FIGURE 19
Areal View of Oasis Settlement in the Interior of Oman, ca. 1975. Source: Fred Scholz.

Agriculture is still a major economic aspect of Oman. Modern farms in climate controlled environments and industrially irrigated proliferate next to traditional farms. Agriculture is intended to thrive in the future as a factor of economic diversification and food security. 182 Today, a complex system assures water access. On top of the traditional falaj water distribution systems, retention dams catch storm water run off and replenish some aquifers. Yet the outtake of water is rapidly depleting aquifers. Along the coastline, fresh water aquifer 'fend-off' is infiltrated by salty sea water. 183 Once this fragile balance is disturbed sea water contaminates previously arable land. The majority of fresh water is now produced industrially using desalination plants running on natural gas. Burning fossil fuels is but one of the ecological problems. Brine water discharge pollutes the adjacent ocean waters. 184

182 Al Said et al., "Profitability Analysis of Selected Farms in the Batinah Region of Oman," 9.
183 Zekri, Al-Rawahy, and Naifer, "Economic Impact of Salinity: The Case of Al-Batinah in Oman."
184 Bleninger and Jirka, "Environmental Planning, Prediction and Management of Brine Discharges from Desalination Plants."

Water distribution relies on motor vehicles instead of pipes since settlements in Oman are comparably loose in density and dispersed across large areas. This factor is a major driver of urban expansion, since water access is now mobile and independent of direct connection to a distribution network (SEE FIGURE 20). Yet, the costs of this mobile distribution are large and the scalability limited. The water production relies on large governmental subsidies. Industrial fresh water production is thus linked to fossil natural gas which is again finite. Solar-powered salt water desalination is not yet scalable. In a post-fossil future fresh water will become expensive (again) in Oman. It will also be necessary to locate future settlements close to sustainable sources of water and link water use and re-use for agriculture closely (again). The present situation divorces the location of water production from its consumption enabling an unprecedented urban sprawl. In future the production and consumption of water will have to be congruent again, thus re-linking the location of agricultural space and urban infrastructure directly to the production of water.

FIGURE 20
Sewerage water transport by trucks across Oman 2014.

Both research on oasis settlements and changing agricultural systems convey the key message that a careful spatial management of water-related land use transformation – residential or agricultural – is key to Oman's future. Dutton states that the changes forced upon the rural systems in Al Batinah were induced from the outside: oil export, migration of labour force, loss of markets are all aspects of an unhindered urbanisation process. If, indeed, the urbanisation process had been an integral part of urban and rural communities, some damage could have been avoided. In this sense, the 'Kaburah Project' holds clues for the development of sustainable agricultural spaces in the future. Scholz' structuralist approach to spatial organisation of oasis settlements can lead to a culturally adapted form of land use and urban design. Finally, Zekri's studies on the economic decline of agriculture based on the conflicting land uses is a reminder that the target land uses of this thesis – residential or agricultural spaces – are highly intertwined, delicate and interlinked and need to be addressed together in light of a sustainable future.

PLANNING STRATEGIES AND PHASES OF URBAN DEVELOPMENT

Urbanisation rates from the UN reveal an urban population of 77,6% in 2015. [185] This figure alone says very little about the process and current state of urbanisation in Oman. The present planning system in Oman is the result of several development and planning strategies authored by foreign planners invited to consult the government of Oman since 1970 (SEE TABLES 1, 2 AND 3). This planning can be described in three distinct phases:

- The first phase relates to the establishment of Muscat and Seeb as dual anchors of the future metropolitan region from ca. 1977 to 1989 and was lead by the planning team of Llewelyn-Davies.
- The second phase relates to the development of Muscat Capital Area from ca. 1991 to 2010 and was lead by the planning team of Weidleplan Muamir and the Ministry of Housing.
- The third, and ongoing phase relates to managing the urban expansion and developing a national spatial strategy for Oman (ONSS). It started in 2010 and is lead by the Supreme Council of Planning and several consultants.

The most influential and finally guiding plans of the first phase included the local plans for Muscat and Seeb, [186] as well as development reports (Llewelyn-Davies 1981a) and the Capital Area Structure Plan [187] by by Llewelyn-Davies. These plans were incorporated into the five-years economic development plans. [188] The resulting plan set and guiding documents can be described as structural zoning. The planning area of the city is conceptualised as an assemblage of spatially separated functional entities:

185 UN ESA, "Growth Rates of Urban Agglomerations by Size Class 2014 to 2030."
186 Llewelyn-Davies, "MRLP."
187 Llewelyn-Davies, "CASP."
188 Development Council, "FYDP," 1986.

Commercial, industrial, residential, transport, military, recreational, etc. These areas are served by vast automobile road networks. Functional modern planning has been widely criticised in the West since the late 1960s (see Jacobs [189]), but is was state of the art in when it came to planning new cities in emerging economies and has often found fertile ground in autocratic regimes that could implement planning strategies immediately and without critique or resistance. Scholz reproduced the Llewelyn-Davies plan in his study on Muscat in 1990 (SEE FIGURE 21).

Master Plan for Muscat and Oman, Wace, 1969
Muscat and Greater Mutrah Development Report, Harris, 1970
Muscat City Planning, Makiya Associates, 1972
Greater Mutrah Master Plan Report, VIAK, 1972
Qurm Development Plan, Gibb and Petermüller, 1974
1st Five Year Development Plan, Development Council, 1976
Coastal Policy Study, Oman Planning, Llewelyn-Davies, 1977a
Mutrah – Ruwi Local Plan: Capital Area Zone two. Preliminary Policies, Llewelyn-Davies, 1977b
Seeb Local Plan, Oman Planning, Capital Area, , Llewelyn-Davies, 1977c
2nd Five Year Development Plan, Development Council, 1981
Development Reports, Llewelyn-Davies, 1981a
Housing Study – Final Report, Llewelyn-Davies, 1981b
Capital Area Structure Plan: Major Road Network and Predominant Land Use, Llewelyn-Davies, 1983
3rd Five Year Development Plan, Development Council, 1986

TABLE 1
Planning studies considered by Scholz up to publication in 1990. [190]

189 Jacobs, *The Death and Life of Great American Cities*.
190 Scholz, *Muscat – Then and Now Geographical Sketch of a Unique Arab Town*, 142–48.

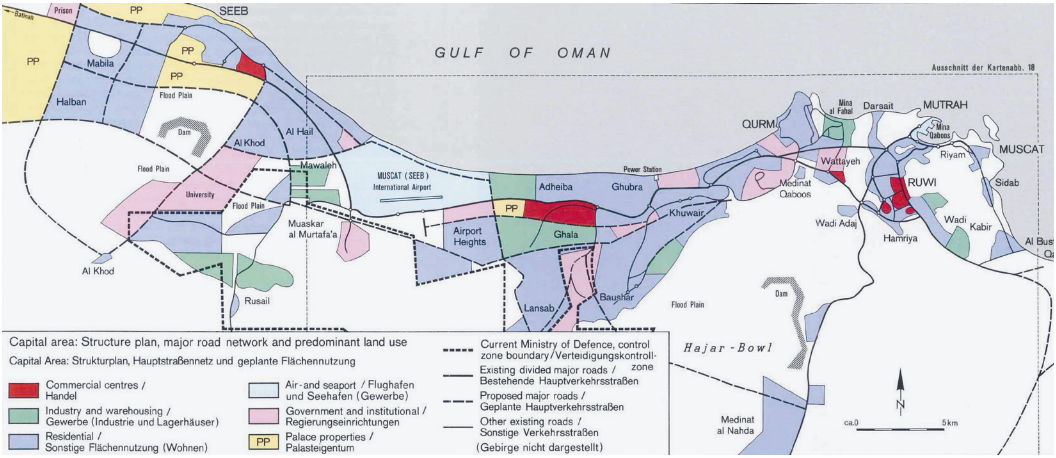


FIGURE 21
Spatial Structure of Muscat Capital Area in 1990. Source (Scholz, 1990).

Planners Manual Part 2: Standards and Guidelines, Llewelyn-Davies Weeks for the Ministry of Land Affairs and Municipalities, 1979
Qurm Development Area – Al Kuwair South, Ministry of Regional Municipalities and Water Resources, 1983
Research about Developing Muscat City – Submitted to Development Committee of Muscat, Ministry of Regional Municipalities and Water Resources, 1985
Oman Coastal Zone Management Plan-Greater Capital Area (English), IUCN, Ministry of Commerce and Industry, 1986
Capital Area Transport Study – Executive Summary (English), Dar Al-Handasah Consultants (Shair & Partners), Diwan of Royal Court, 1987
Muscat Regional Plan (English), Weidleplan and Muamir, Ministry of Housing, 1989
Muscat Area Structure Plan (English), Weidleplan and Muamir, Ministry of Housing, 1990
Batinah Regional Plan, Ministry of Housing, 1991
Rustaq Structure Plan, Ministry of Housing, 1991

TABLE 2
Sources not included by Scholz in circulation or in preparation with local planning authorities up to 1990.

Development Project for Rustaq City (English, Arabic), N/A, Ministry of Regional Municipalities and Water Resources, 1993
Visions to Promote the Economy Perceptions in Al-Batinah Region, Introduction by Businessmen in the Region (Arabic), N/A,
Regional Development in the Sultanate of Oman (Current Model) (Arabic), Dr. Rasoul Faraj Al Jabri – Regional Planning Expert,
Guide to Physical Planning (Arabic), Supreme Committee for Town Planning, 2003
Corridor and Alignment Study of Batinah Coastal Road – Volume 2: Drawings (English), Parsons International & Company LLC,
Sustainable Development Indicators (English, Arabic), Statistical Advisory Committee, Ministry of National Economy, 2006
North of Al Batinah Master Plan Region 2025, Port of Sohar and Port of Rotterdam, Ministry of Transport & Communications, 2007
Master Plan: North Batinah Region 2025 – Choosing Wealth, Quality & Diversity – Base Document (English), Port of Sohar, Project Team Port of Rotterdam, Sohar Industrial Port Company, Muscat Branch Office, Ministry of Transport & Communications, 2007
The Future Industrial Strategy for the Sultanate (Arabic), N/A, Ministry of Commerce and Industry, 2008
Aflaj Oman in the World Heritage List (English, Arabic), N/A, Ministry of Regional Municipalities and Water Resources, 2008
Mutrah Redevelopment and Masterplan (Stage 2 Reports and Working Papers), NORPLAN A/S, WSP and German University of Technology, Muscat Municipality and Haya Water, 2011.
Comprehensive Master Plan for Al Batinah Coastal Area, HMR Consultants, LEA, Perkins and Will, Supreme Council for Planning, 2013

TABLE 3
Additional sources of planning analysed by the author in a review of the third phase of urban development in Oman leading to the ONSS.

Archival research shows that Scholz did not include other studies conducted at the same time, in particular the Weidleplan Muamir plans of 1989–91 as well as other studies focussing on regional development of other centres, coastal development, transport and regional planning. Scholz' geographic 'sketch' of Muscat contained 80 diagrams, 64 photographs and detailed six detailed urban maps. The second part covered the geographic features, concepts of urban expansion, zoning and infrastructure, functional differentiation and socio-geographic processes and patterns. Scholz' geographic approach can be considered 'structuralist'. According to Aitken and Valentine structuralism in geography is understood as" *"A theoretical approach to human geography which is characterized by a belief that in order to understand the surface patterns of human behaviour it is necessary to understand the structures underlying them which produce or shape human actions."* [191] This geographic

191 Aitken and Valentine, "Ways of Knowing and Ways of Doing Geographic Research," 342.

school of thought is associated with linguistic studies and in particular structural anthropology and Marxist structuralism. Structuralist geography expands the *French sociologist Pierre Bourdieu's 'Theory of Power and Practice'* and Theory of *'Social Space, Capital & Field'*. 192 Structuralist geography supposes that socio-cultural structures within society shape individual behaviour in a causal way rather than by individual motive and interpretation: *"[…] the relation of structure and social practice is dual, meaning that social practices refer to social structures and that social structures are the result of previously performed practices and social actions."* 193 The critique of structuralism gave rise to 'post-structuralism' – a concept that rejected structuralism. The main arguments against the structuralist are the self-evidence and self-referentiality of the underlying structures that also apply to structuralist geography. The way forward is to 'de-construct' the underlying assumptions and to expose their components without casting them into a pre-conceived mould or hierarchical structure system. 194 Scholz started by a meticulous analysis of geo-morphological, climatic and hydrological conditions to support his socio-cultural analysis. *"The areas in which the Capital Area was to unfold extends form Bustan and/or Qantab in the east to Seeb in the west, and also reaches inland wherever the relief allows this. In very broad terms the relief can be subdivided into two parts: eastwards from Ras al Hamra rise the mountains, whilst the plain extends to the west."* 195 This geo-morphological setting will become the supporting structure for Scholz' description of Muscat Capital Area. Scholz applied the same structural analysis to social and political aspects of Oman. This argumentation served to underline his spatial structural analysis later: "*The tribes of Oman's extensive hinterland, which since the 18th century had been divided into the Ghafiri and Hinawi faction* 196 *and which were to varying and changing degrees connected with the Al Bu Said [royal] family which had ruled since 1749, and which were consequently not involved to the same extent in the civil war-like conflict between the sultan and the imam in the 1950s, were not at all prepared to recognize unreservedly the young sultan's claim to power."* 197 He describes various actor groups such as tribal leaders, urban merchants, returned Omanis

192 Lippuner and Werlen, "Structuration Theory," 5.
193 Lippuner and Werlen, 1.
194 Woodward, Dixon, and Jones, "Poststructuralism/Poststructuralist Geographies."
195 Scholz, *Muscat – Then and Now Geographical Sketch of a Unique Arab Town*, 138.
196 Wilkinson, *Water and Tribal Settlement in South-East Arabia*, 223.
197 Scholz, *Muscat – Then and Now Geographical Sketch of a Unique Arab Town*, 9.

and their aspirations that, according to his structural model and the distribution of economic and political forces within the given terrain, 'inevitably' gave rise to the urban development as seen later.

While the meticulous documentation and impressive presentation of Scholz' findings has its merit and forms a base for this dissertation, the structuralist approach remains limited. The structuralist model seems to fit the hierarchies of the Omani political system all too well. Even though the Sultan of Oman has been in power for more than 45 years, the socio-political system is changing. Marc Valeri has carefully deconstructed the social and economic changes that pressure the feudal state to change not just after the so called Arab Spring in 2011. 198

Scholz' model also needs to be questioned with respect to the simplistic causal relation of agents and actions. Society and motivations in the 1980s were different than today. Finally, the scope of observation of Scholz concurs with the planning schemes he assisted in carrying out, namely the *Capital Area Structure Plan: Major Road Network and Predominant Land Use* designed by Llewelyn-Davies in 1983 which determined the future zoning of Muscat Capital Area. 199 This plan was backed by comprehensive calculations on expected inhabitant numbers, housing requirements and road infrastructure. Scholz' own predictions on the urban development of Muscat are thus limited to diagrammatic projections about 'dual centres' and sub-centres along the Al Batinah coast. This plan had a temporal scope of 20 years from 1983 and has been outdated since the 2000s.

In defence of Scholz' one can argue that he did not have access to high-resolution satellite images or classified military maps to further support his structural model of urbanisation. These documents are now available and have been included by the author to revisit the urbanisation process of Oman (See also the section on previous research by the author). Finally, Scholz' project of urban geography of Muscat is still relevant as this thesis aims to demonstrate. In a post-structural critique it aims to expose the different knowledge systems that produce the diversity of the present urbanisation of Oman. In contrast to Scholz' deterministic

198 Valeri, "An Omani Economic Dilemma"; Valeri, Oman; Valeri, "Domesticating Local Elites. Sheikhs, Walis and State-Building Under Sultan Qaboos"; Valeri, "Simmering Unrest and Succession Challenges in Oman."

199 Llewelyn-Davies, "CASP."

view, which casts a highly structured look at the process and leaves little space for alternative urbanisation models, this dissertation aims to extract parameters of sustainable urbanisation out of a more differentiated study of urbanisation in Oman itself.

The 1991 Muscat Area Structure Plan by Weidleplan and Muamir marks the second phase of urban development of Muscat Capital Area from 1991 to ca. 2010. This elaborate set of documents (studies, plans, strategies, zoning and regulations) detailed much of what was laid out previously by Llewelyn-Davies with new target development milestones for 2010. The plan aimed to consolidate the larger capital area as one extended urban network while maintaining the existing structural layout and functional division. Due to the increased demographic pressure the Ministry of Housing Oman (MoH) was the main governmental supporter of this plan. Housing became synonymous with urbanisation during this phase of development to which Weidleplan dedicated three of their nine reports in total. [200]

Urban geographers grew interested in the consequences of the second phase of urban development by the late 2000s: [201] Al-Awadhi produced a first remote sensed map of the urbanisation process of Muscat Capital Area. The discussion of this map gave till then still vague phenomenon of urban sprawl in Oman a first spatial shape. The geographer Belgacem developed a theory of coastal growth vectors applicable to Oman and other Gulf countries that he termed 'litoralisation'. [202] The agronomist Zekri studied profitability of agricultural production and salination threat in relation to urban development in Muscat Capital Area and the Al Batinah region. [203] These studies started to question the official narrative of limitless and lasting growth as reported in the vision 2020 document prepared on behalf of the Supreme Committee of Town Planning (SCTP, dissolved in 2012 to become the become the Supreme Council of Planning, SCP). [204] Al Gharibi wrote his doctoral thesis on urban growth in Muscat with recommendations towards a more sustainable approach. He Al Gharibi focussed on the urban transformation phase that happened from 1990–2014, critically evaluating planning strategies of the Ministry of Housing Oman. [205] He also conducted various stakeholder

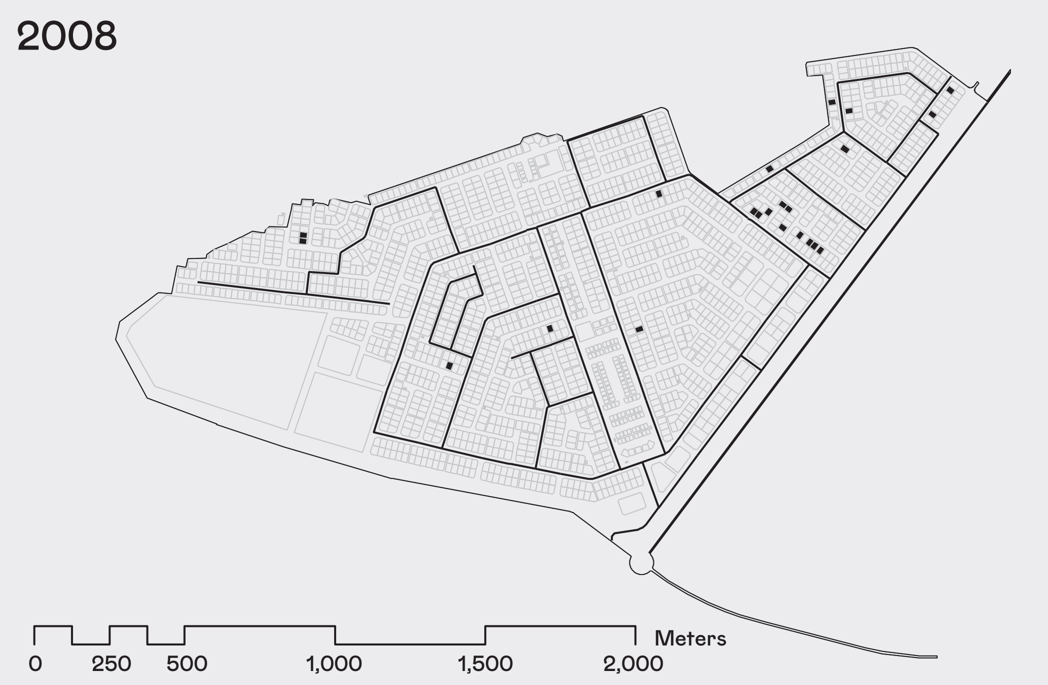
200 Weidleplan, "Muscat Area Housing Study Phase 3 Report 4."
201 Al-Awadhi, "Monitoring and Modeling Urban Expansion Using GIS & RS."
202 Belgacem, "Is Littoralization Reconfiguring the Omani Territory?"
203 Al Said et al., "Profitability Analysis of Selected Farms in the Batinah Region of Oman"; Zekri et al., "Food Security as a Public Good: Oman's Prospect"; Zekri, Al-Rawahy, and Naifer, "Economic Impact of Salinity: The Case of Al-Batinah in Oman."
204 Royal Decree: Vision 2020.
205 Al Gharibi, "Urban Growth from Patchwork to Sustainability Case Study: Muscat."

interviews to qualify the urbanisation process. Al Gharibi invokes current sustainability models that do not necessarily apply to the case study in Oman in response to the still unresolved question of housing. He criticises that the urbanisation process of the 1990s lead to an extended urban sprawl. Al Gharibi argues that sustainability measures can lead to more efficient land use and energy savings and that these in return can lead to a better land allocation.

Al Shueli meticulously traced all official planning strategies, their genesis, scopes, contradictions and (partial) implementation in Oman, throughout the decades. 206 He used systematic interviews that are coded and form an important source of his dissertation. Through these various stakeholder perspectives, he was able to construct an image of the urbanisation process during the 2000s. Al Shueli concludes that the intentions of the Omani government were correct, but that the various plans were not implemented accordingly due to lack of urban governance structures. Both dissertation deserve merit because they made Arabic source material accessible to the non-Arabic academic community. Both dissertations state that the current process of urbanisation is not sustainable. Unfortunately, neither dissertation maps the urbanisation process nor quantifies measures for a sustainable future.

The Research Council that founded the project 'Urban Oman' (lead by the author and Dr. Sonja Nebel at the German University of Technology in Oman, GUtech) with partners from the Sultan Qabous University (SQU) investigated the patterns of urbanisation for the first time since Scholz' studies of 1990. This four-year research project allowed to conduct long term observation of urbanisation patterns, in particular housing, in neighbourhoods in Muscat Capital Area and on the rural-urban interface. The two case studies chosen were the new neighbourhood of Al Khoud and the transforming oasis village of Fanja. The author examined urban expansion of new residential areas and presented a first 'tool-box' for future sustainability models. 207 This temporal and spatial long-term study of an easily accessible site in Muscat Capital Area allowed to gain valuable insights and validate many research hypothesis' namely that the present land-transformation process is neither efficient, nor fair, nor socially or ecologically acceptable, in short, highly unsustainable (SEE FIGURE 22).

206 Al Shueili, "Towards a Sustainable Urban Future in Oman: Problem and Process Analysis."
207 von Richthofen, "Patterns of Urban Growth and Expansion: The Al Khoud Case Study"; von Richthofen, "Parameters of Urban Expansion in Oman."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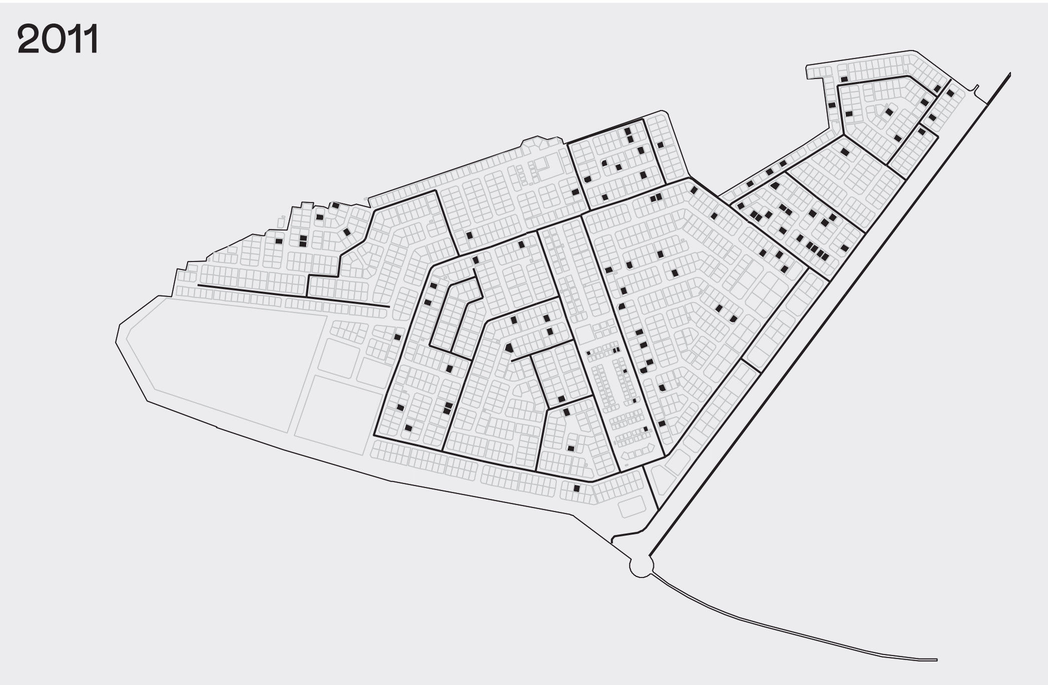

2011

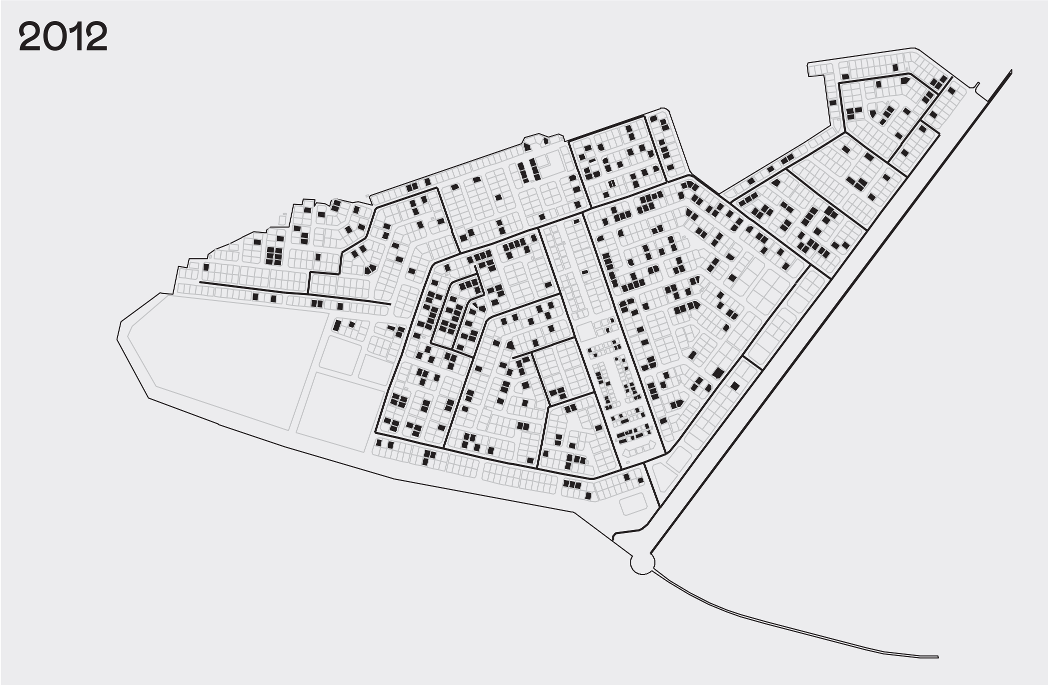


FIGURE 22
Land settlement processes as observed in Al Khoud 2008–2013. 208

208 Nebel and von Richthofen, Aurel, *Urban Oman – Challenges, Trends and Perspectives*.

During this time the idea of a parametric urban model emerged, 209 but just a rudimentary prototype was implemented as a proof of concept as the underlying spatial mechanisms were not yet understood and methods for research adapted to Oman, in particular the absence of reliable spatial data and their automatic acquisition, were still in their infancy. The research empirically confirmed the theoretical postulation of a rapid urbanisation process, its driving forces, mechanisms and expected spatial patterns, through ground surveys, residential questionnaires, photographic records and remote sensing using satellite images. It formulated a first approach to urban sustainability in the Omani context. 210 The co-authors recommended to establish a council for sustainability to develop *"targets and indicators for monitoring sustainable urban development and thus giving advice to the Omani government where to set priorities towards a sustainable Oman."* 211 They further argued that decentralised and participatory decision making, a land allocation reform, better land management and monitoring systems, integrated urban planning and better neighbourhood design, consideration for the rural-urban interface, as well as protection of the ecosystems are urgently needed. 212

The project lead to academic exchange, 213 an international conference called on 'Challenges of Urbanization in Arab Gulf Countries', 214 a travelling exhibition 'Urban Oman' in Muscat, Aachen and Berlin, 215 a website 216 and a book 'Urban Oman – Trends and Perspectives of Urbanisation in Muscat Capital Area'. 217 In sum, the Urban Oman project contextualised a specific Omani urbanisation process that had by the time of publication of the book exceeded the planned goals of the 1991 Weidleplan strategy and the 1996 Omani Vision 2020.

209 von Richthofen, "Modelling Low-Rise High-Density Neighbourhoods in Oman."
210 Nebel and von Richthofen, "Urban Sustainability in the Omani Context."
211 Nebel and von Richthofen, Aurel, *Urban Oman – Challenges, Trends and Perspectives*, 253.
212 Nebel and von Richthofen, Aurel, 257.
213 von Richthofen, "Focal Point for ETH Studio Basel in Oman."
214 Nebel and von Richthofen, "Conference Organization: Challenges of Urbanization in Arab Gulf Countries."
215 von Richthofen, Eaton, and Nebel, "Exhibition Curated: Urban Oman Exhibition"; von Richthofen and Nebel, "Urban Oman – Booklaunch and Exhibition Vernissage."
216 Nebel and von Richthofen, "UrbanOman.Org."
217 Nebel and von Richthofen, *Urban Oman – Trends and Perspectives of Urbanisation in Muscat Capital Area*.

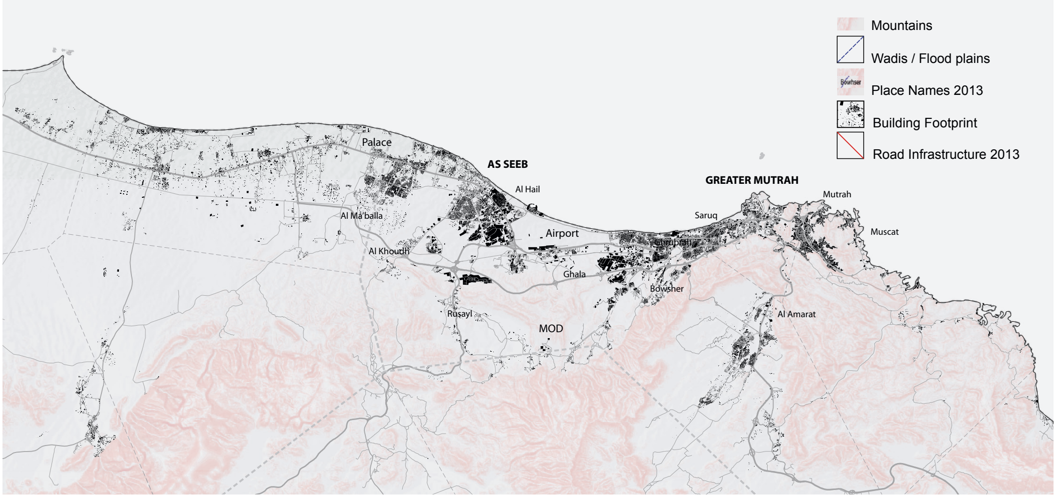


FIGURE 23

Map of Urbanisation Patterns in Muscat Capital Area in 2014. Source (Nebel and von Richthofen, 2016)

FIGURE 24

Areal View of Muscat Capital Area representing the 2nd phase of urbanisation in Oman, 2014.

Following the Urban Oman project research efforts were directed towards the third and ongoing phase of urbanisation in Oman (SEE FIGURE 23 AND 24). The official narrative of this phase is still being shaped as the ONSS is under way and cannot yet serve as backdrop for a substantial critique yet. The ONSS team is asking the following questions: *"Where is the best suitable space for the expected growing population and further diversified economic activities? How can all kinds of infrastructure, such as roads, public transport, electricity, water and sewage, be more effectively be integrated into new urban developments? What kind of vulnerable areas need better protection? How to anticipate on climate change and what is needed to deal successfully with the coming post-oil era? And how can Oman combine all its ambitions and challenges in a sustainable way?"* [218] The ONSS links ecological to socio-economic development. It aims to use regionally adapted strategies as 'building blocks' for the national strategy while focussing on the themes of *"people and society, economic development and governance"*. It draws from an *"extensive data collection exercise on all kind of information related to social, economic and land use aspects"* to develop national scenarios to be adopted by the Al-Shura and the Council of State later. [219] These questions are being underlined with scientific research and new methods. These methods, in return, shape the spatial reasoning and representation.

To date, comprehensive information about the present land use structure and capacity of Oman is not available. The socio-cultural, urban-geographic, mobility-related and spatial aspects of urbanisation in Oman are just now being examined.

A cooperation with the urban planning department of the northern Omani city of Buraimi and Technische Universität Berlin (TU Berlin) by Nebel and Salcedo proposed 'A Strategic Approach towards Integrated Urban Development and Resilient Urban Management' in a regional city of Oman. [220] Research by the author in several publications and the organisation of international workshops in Cambridge in 2016 on the occasion of the Gulf Research Meeting aimed at broadening the scope of urban research on Oman. [221] Conference participant Scholz examined climate

218 Supreme Council of Planning, "National Spatial Strategy in Oman."
219 Supreme Council of Planning.
220 Nebel and Salcedo, *Al Buraimi, A Strategic Approach towards Integrated Urban Development and Resilient Urban Management*.
221 von Richthofen, Deffner, and Babar, "Conference Organization: Arab Gulf Cities in Transition: Space, Politics and Society."

sensitive urban design and changing mobility in Muscat by Jafary and Scholz, 222 whereas Tomarchio examined social media data to determine the use of urban space. 223

The author and Langer developed a remote sensing method to track changes in land use and determine urban expansion patterns and land suitable for urban expansion. 224 The authors found that the land use was dramatic and reached tipping points. The author and Heim, Joosten and Rupp developed an agent-based model to simulate economic and social behaviour of recipients of the land allocation lottery system in Oman. 225 The authors found that the system can never reach the desired goal of complete land allocation, distorts the market and leads to land speculation, ultimately undermining the welfare character of the system. They recommend urban management strategies to mitigate the effects. Several authors mobilise social and geographic theory to question the prevailing growth model of Oman. In contrast to city-centric urbanisation phenomena in the Gulf with cities such as Dubai, Abu Dhabi and Doha that experienced stellar growth, Oman seemed to offer an interesting case study to prove the concept of 'Regionalization'. Wippel examined the economic and political context of urban development strategies in Oman. He later applied these concepts to other Gulf cities to gain a differentiated socio-dynamic perspective on the growth process. 226 The geographers Deffner and Pfaffenbach studied migration and migrant work as a key component of contemporary urban production. 227

As stated by the author and co-authors with respect to the current mode of land allocation by lottery and the prevailing residential model in Oman:

222 Jafari and Scholz, "Towards Sustainable Urban Development: Challenges and Chances of Climate-Sensitive Urban Design in Muscat/Oman."
223 Tomarchio, "Mapping Human Landscapes in Muscat, Oman, with Social Media Data."
224 von Richthofen and Langer, "Evaluating the Urban Development and Determining 'peak-Space' of Muscat Capital Area."
225 Heim et al., "On the Process and Economics of Land Settlement in Oman: Mathematical Modeling and Reasoning in Urban Planning and Design."
226 Wippel, *Regionalizing Oman Political, Economic and Social Dynamics*; Wippel et al., *Under Construction*; Wippel, "Salalah Globalized: Developing, Fragmenting, and Marketing a 'Secondary City' at Spatio-Temporal Interfaces."
227 Deffner and Pfaffenbach, "Integration auf Zeit für ein Leben in Transition"; Carmella Pfaffenbach and Deffner, "Migration, Modernisation, and the Urban Immigration Society in the Sultanate of Oman."

– *"Possible remedies based on the results of this simulation may include:* **(1)** The development of a land monitoring system based on the simulation results. *Currently, the Ministry of Housing has the sole authority to distribute land and has not yet installed an effective land monitoring system. Next to a Geographic Information System (GIS) database, an urban simulation can lead to an evidence-based urban design and ultimately improve the current land allocation system.*
– **(2)** Modification of the pricing policy for land allocation and the introduction of variable pricing to steer land use and counteract land-speculation. *In principle, the pricing policy has not changed since 1990, and land is still allocated by the lottery system to all Omani citizens. The fees paid by the applicants do not currently cover the development costs incurred by the government nor do they reflect market prices. The simulation results question the efficiency of the system and reveal negative side effects such as land-speculation.*
– **(3)** Procedures to identify and predict genuine demand and suitable prioritization of allotments based on the simulation results. *The pricing policy drives an excessive demand for land, making it impossible to identify genuine demand.*
– **(4)** Coordination with other agencies responsible for the provision of infrastructure. *Coordination with other agencies has not significantly improved since 1990. The asynchrone development has many causes that defeat the goal of higher achievement rates.*
– **(5)** Strengthening housing finance institutions based on an economic simulation model. *This is evident in the wide range of low interest mortgage schemes in operation.*
– **(6)** Creating provisions for re-acquisition of plots by the Ministry of Housing. *Provisions for re-acquisition of plots have been created and the land granted to residents can be reclaimed with appropriate compensation.*
– *Finally, one may* **(7)** consider individual household preferences and resident satisfaction. *The master planning does not take into consideration individual household preferences nor resident satisfaction. Residents are gradually losing touch with traditional ways of life and local customs as they move into newer neighbourhoods."* [228]

Finally, this dissertation aims to tackle spatial development for a sustainable future in Oman in light of the fact that the 'Renaissance' model is in crisis. ●

228 Heim et al., "Land-Allocation and Clan-Formation in Modern Residential Developments in Oman."

PART

III

METHODS AND DATA

PART 3: METHODS AND DATA

The methods section describes the data, tools and approaches used to answer the research questions. Available data on land use transformation in Oman is very poor and even if it exists needs to be questioned carefully. This thesis uses remote sensing of spatial information based on satellite images to create a database for research. The methods of remote sensing and the implications for the case of Oman are discussed. This data forms the base for measuring spatial diversity. An index is then built by considering the theoretical aspects of production of space, extended urbanisation, urban metabolism and finally spatial diversity.

DATA SOURCES AND GAPS

The research starts with the careful collection and study of legal documents such as building codes, planning standards and structure plans that regulate the spatial configuration of Oman. It is necessary to triangulate official data (or the lack thereof) with data from international agencies and non-governmental organisations (NGOs), social media and consultant reports. It is possible to read and question official statistics and census data by comparing values across time and across category for data consistency and clarity. It is also possible to dis-aggregate certain types of aggregated data to shed light onto more detailed spatial zones of investigation. The research literature, mostly in English, German and French, has been collected in a referencing database 'Zotero' (see chapter State of the Research above and Bibliography at the end). While Arabic sources could not be read by the author most of the official documents in Oman are available in English. Next to official documents, consultant reports offer a great source to understand the motivation and drivers of specific development plans. While these documents are carefully prepared they are not scientific documents but rather commercial service provisions.

DATA TRANSPARENCY

According to the Bertelsmann Stiftung, media are controlled by the state in Oman. [229] Censorship including withholding of 'negative' articles on topics such as economic failures, planning delays, lack of reform or vague development vision, is practiced.

229 Bertelsmann Stiftung, "BTI 2016 – Oman Country Report."

This censorship also includes the publication of maps and the release of geo-spatial information. Data transparency was not practiced in Oman at the time of research and national standards to enter data were missing. Conventional touristic maps issued by Omani authorities are deliberately vague and abstract. Military installations are typically omitted from these maps, yet large parts of the territory of Muscat Capital Area the governorates (provinces) of Al Batinah and Muscat itself are still under military use. Location names tend to be confusing as several transliteration versions exist. Touristic maps concentrate on the centres of the agglomeration and ignore the outer fringes. They are ambiguous with respect to what has been built and what is still in the planning stage. Due to the fast pace of urban development, large areas reserved for future planning often are included in maps while they are hardly built-up in reality, with roads appearing in dashed lines indicating an anticipated completion date.

GLOBAL DATA SOURCES

Increasing availability of international geo-spatial data forms a new source for inquiry and remote sensing. Satellite imagery is available from many sources such as the ESA Earth Online catalogue [230] and the United States Geological Survey. [231] These satellite images form a raw database that can be interpreted either visually or automatically with tools for image interpretation. Satellite images are to a varying degree available for past records. Another underexploited source of geo-information are historic military maps that were prepared during certain timeframes and accurately represent the geo-spatial setting of that time. These large datasets have the advantage that they are uniformly available for the whole planet, are freely accessible, but come at reduced spatial resolution. The datasets used for this study have a spatial resolution of 15×15 m, which excludes fine-grain urban and agricultural analysis. Any object smaller than the resolutions threshold risks being overlooked or wrongly classified. The qualitative interpretation derived from data is therefore crucial.

During the time of research for this dissertation many such derivates appeared. Hansen developed ‘High-Resolution Global Maps of 21st-Century Forest Cover Change’ using 30×30 m resolution Landsat data. [232] Their global survey covers the period from

230 European Space Agency, “ESA Earth Online Catalogue.”
231 United States Geological Survey, “Data and Tool Topics.”
232 Hansen et al., “High-Resolution Global Maps of 21st-Century Forest Cover Change,” 850.

2000 to 2012 and can be viewed online at the Global Forest Change site. Hansen examined only the tree canopy cover at the Landsat pixel scale. They excluded other forms of vegetation and agriculture in particular. The study by Hansen and co-authors explicitly excludes the Omani date palm plantations and the periodic rain forest of Salalah in the south of Oman, that do provide a significant tree canopy. This thesis uses the same 30*30 m resolution Landsat data to map the Omani agricultural and naturally vegetated areas from the 1980s onwards, 233 The United Nations and the European Space Agency published *'Growth Rates of Urban Agglomerations by Size Class 2014–2030'*. 234 The World Bank commissioned a large scale study on *'East Asia's Changing Urban Landscape: Measuring a Decade of Spatial Growth'*. 235 This demonstrates the technical feasibility of tracking spatial expansion by using satellite imagery on a continental scale. More international research centres use the potential of remote sensing such as the London School of Economics project on *'Resource Urbanisms – Natural resources, urban form and infrastructure in the case of Asia's diverging city models'*, 236 and the studies on the Asian extended metropolis in data-poor settings including a prototype geo-spatial visualisation tool *'UR-Scape'* 237. Despite this growing effort by the international research community suitable and processed data for Oman was not available.

OFFICIAL DOCUMENTS AND DATA

Three documents regulate the built-up environment of Muscat Capital Area: The Building Code, 238 the Physical Planning Standards 239 and the Structure Plan developed by Weidlepan. 240 Together these documents cover the volumetric aspects of a building within a plotline, the urban planning aspects on a larger scale, and the zoning and phasing locations for implementation. The limitations of this triangular system of 'building code

233 "Landsat."
234 UN ESA, "Growth Rates of Urban Agglomerations by Size Class 2014 to 2030," 30.
235 The World Bank, *East Asia's Changing Urban Landscape: Measuring a Decade of Spatial Growth*.
236 Rode, Gomes, and Adeel, "Resource Urbanisms – Natural Resources, Urban Form and Infrastructure in the Case of Asia's Diverging City Models."
237 Cairns et al., "Bandung Smart Systems"; Cairns, "Urban-Rural Systems in Asia: A Research Agenda"; Cairns, Neudecker, and Joos, "UR-Scape."
238 Muscat Municipality, "Building Regulation for Muscat – The Sultanate of Oman."
239 Atkins Int., "Physical Planning Standards."
240 Weidleplan, "Muscat Area Structure Plan Phase 3 Final Report."

– planning standard – structure plan' and a discussion of the problematic results and consequences for Muscat Capital Area and Oman has been undertaken by Al Gharibi, AL Shueili, Nebel and von Richthofen. 241

Similar building codes, planning standards and zoning documents have been studied for neighbouring countries (UAE, Bahrain, Kuwait) to establish references. To overcome the limitations of the tripartite 'building code – planning standard – structure plan' the Abu Dhabi Urban Planning Council developed a 'form-based code' that is still the most advanced in the region at the time of study. 242 The critique of Abu Dhabi's form-based code inspired modelling of a more sustainable low-rise high-density neighbourhood for Oman. 243 The Abu Dhabi Urban Planning Council also developed a sustainability rating system called 'Estimada'. 244 This system competes with Dubai's 'Green Building' regulations. (Dubai Municipality 2013) A detailed account of the sustainability systems in comparison to European and American systems and their role in the sustainability discourse has been rendered by the author in the article 'Urban Sustainability as a Political Instrument in the Gulf Region exemplified at Projects in Abu Dhabi'. 245

The government of Oman publishes the annual Oman Census. 246 It breaks down data into national, regional and provincial levels for the categories of 'Population, Households and Housing Units', 'No. & Percentage Distribution of Housing Units', 'No. & Percentage Distribution of Households (Omani – Expatriate)', 'No. & Percentage Distribution of Population (Omani – Expatriate)', 'Distribution of Population (Omani/Expatriate)'. International sources include UN statistics and reports. 247 Country

241 Al Gharibi, "Urban Growth from Patchwork to Sustainability Case Study: Muscat"; Al Shueili, "Towards a Sustainable Urban Future in Oman: Problem and Process Analysis"; Nebel and von Richthofen, Aurel, *Urban Oman – Challenges, Trends and Perspectives*, 26.
242 Abu Dhabi Urban Planning Council, "Estidama."
243 von Richthofen, "Modelling Low-Rise High-Density Neighbourhoods in Oman," 189.
244 Abu Dhabi Urban Planning Council, "Estidama."
245 Cummings and von Richthofen, "Urban Sustainability as a Political Instrument in the Gulf Region Exemplified at Projects in Abu Dhabi."
246 Oman Census, "Oman Population Census."
247 UN HABITAT, "An Urbanizing World – Global Report on Human Settlements 1996"; UN HABITAT, "The State of the Arabian Gulf Council Cities (Sultanate of Oman)"; United Nations Statistics Division, "UN Data – Oman"; The World Bank, *East Asia's Changing Urban Landscape: Measuring a Decade of Spatial Growth*.

profiles, and reports produced by non-governmental organisations (NGO) include the 'Country Report – Oman' prepared by BTI. 248 The NGO proposes a democracy 'transformation index' for recent years. This is an aggregated indicator for social, economic and political development. This indicator cannot be directly translated to urban development, but it helps to position Oman within the Gulf and beyond. Governmental information, notably the Omani National Centre for Statistics offers annual reports and bulletins that contain population, census and development indicators. 249 This data is aggregated to the level of provinces. Due to the restructuring of administrative boundaries in 2011 and before temporal comparison is not possible. 250 Previously, Oman was administered in five regions (mintaqah) and four governorates (muhafazah), totalling nine administrative zones. Presently, Oman has eleven governorates (muhafazah). Al Batinah was previously a single region and is now split into two parts: Al Batinah North and Al Batinah South Governorates. The boundaries of Oman's 61 provinces (wilayat) have been corrected accordingly. Furthermore, Oman started counting expatriates residents as population in 2012 and not before. The census data is thus difficult to interpret both temporally and spatially. The Economist Intelligence Unit 2008 and Oxford Business Group prepared country profiles based on a system of metrics that are updated on a yearly basis. 251 These reports have to be critically questioned since the official census in Oman recently changed the administrative boundaries and the counting methods, a concept that is challenged by the discourse on extended urbanisation.

Several authorities in Oman use spatial data. The military certainly has extended geo-information but does not share it with other authorities or the public. Multiple enquiries were made by the author and colleagues researching on urbanisation in Oman for previous research and consultancy projects with The Research Council Oman and for the Oman National Spatial Strategy without success. 252 In fact, the main deliverable of the Oman National Spatial Strategy is supposed to be a harmonised and accessible

248 Bertelsmann Stiftung, "BTI 2008 – Oman Country Report"; Bertelsmann Stiftung, "BTI 2010 – Oman Country Report"; Bertelsmann Stiftung, "BTI 2012 – Oman Country Report"; Bertelsmann Stiftung, "BTI 2014 – Oman Country Report"; Bertelsmann Stiftung, "BTI 2016 – Oman Country Report."
249 National Centre for Statistics & Information, "Oman Census."
250 "Seven New Divisions Created in Oman."
251 Economist Intelligence Unit, "Oman Country Profile"; Oxford Business Group, *The Report*, 2010.
252 von Richthofen and Scholz, "Oman National Spatial Strategy (ONSS) with Focus on Urbanisation."

GIS data base of available data sets in Oman. The Ministry of Housing (MoH) and Muscat Municipality require spatial information for planning, but don't share any such available information either. A visit to the MoH revealed that the only data was stored in a single cumbersome AutoCad file, technically accessible by a single planner at a time. Data entered in this Computer Aided Design (CAD) system had no geo-spatial reference anymore. Cadastral metadata was entered inside the properties table of geometric features which makes it impossible to extract it systematically. Data from this CAD file could hardly be exchanged and proved unusble for the study. The existing data used in Oman was not accurate and contained redundant or contradictory information. Furthermore, there is still no consensus or policy to share this data, neither amongst the authorities nor with the general public.

PRESS AND INTERNET SOURCES

All governmental decisions are published in the national newspapers. These store their articles online in free and accessible archives. Newspapers are often the only indication of a governmental plan, change in legislation, consultancy appointment and tender award. The media landscape in Oman is strictly controlled and there are no competing newspapers with radically different views. The national online newspapers consulted included Times of Oman, Muscat Daily and Oman Observer. Information gathered related to development plans, real estate prices, population statistics, gas prices, water supply and development prospects. Due to the controlled traditional media, internet sources, blogs, social media data become increasingly important. Blogs and social media need to be treated carefully due to the inherent bias of these sources. [253] A big data approach to social media can reveal information about temporal and spatial use of places. [254]

CONSULTANT REPORTS

Sources for urbanisation processes in Oman are often produced as commissioned studies for governmental authorities. These are not published and generally only available to other consultants on a project base.

253 Windecker, “Medienbuch Oman.”
254 Tomarchio, “Mapping Human Landscapes in Muscat, Oman, with Social Media Data.”

SITE OBSERVATION

Muscat and Oman is the living laboratory for this study. Due to the large distances to cover, car-based excursions across the city along the main highways and to specific destinations and neighbourhoods were conducted regularly. The highway rides were filmed with a Go-Pro camera attached to the vehicle at a time when google streetview was not available. The case study Al Khoud, a recently developed, state-planned neighbourhood in Oman, was visited each yearly quarter of the year. On site, the author sketched urban spaces, photographed people, streets vegetation and buildings, measured street-widths and counted houses. The site observation also served to ground-truth information gained from remote sensing with satellite images. The immediate scale also allowed to distinguish building typologies, construction phasing, material, interim use and building material, water and energy consumed during the process. The site visits were further tracked by GPS to record tracks and geo-locate images taken. [255]

DATA GAPS

The key data in this dissertation is data necessary to describe land cover change in Oman in a satisfying resolution. At the time of research this data was not available. Yet, the research question per se demands a kind of data that would hardly be available in other places as well, namely a unified and consistently interpreted dataset for the land use transformation in Oman focussing on residential and agricultural spaces and reaching back significant time spans. It is therefore necessary to establish a consistent geo-data base of land use transformation for Oman that covers a significant temporal scale to answer changes in spatial diversity and to link to those to urban sustainability and resilience in Oman and to develop a suitable interpretation method. This dataset can then be triangulated with information derived from desk studies and ground-truthed by site observation.

255 von Richthofen, "Patterns of Urban Growth and Expansion: The Al Khoud Case Study," 83.

REMOTE SENSING LAND USE TRANSFORMATION

The methods described in this section detailed how the mapping of land use transformation in Oman was conducted. The production of maps and diagrams contribute to the quantification and description of land use change in Oman. The extended urbanisation of Oman has not been mapped scientifically nor adequately for research and planning purposes. [256] Detailed spatial and temporal documentation of the urbanisation process in forms of maps is still not available. The remote sensing process starts with identifying key aspects to map. Based on the literature review the two most urgent and interrelated aspects are housing or residential development and agriculture. The method addresses these two aspects in particular and overcomes challenges associated with the available satellite data and interpretation. Encouragement to engage in this emerging field comes from respected authors: *"Given such progressive data policies and image processing capabilities, it is now possible to use advanced computing systems* [...] *to efficiently process and characterize global-scale time-series data sets in quantifying land change."* [257]

Remote sensing describes the process of extracting information remotely and not by direct observation such as by ground surveys. Satellite data, per se 'just' pixelated data, needs to be interpreted to form information that can later be transformed into maps. The quality of remote sensing data is determined by spatial, spectral, radiometric and temporal resolutions, of which the spatial and spectral resolutions are crucial for this mapping project. Remote-sensing was used in this dissertation for the first time to classify all land cover for all of Oman for the first time and to further extract regional and local land cover maps in regular time points.

Methods to automatically model land use change have been developed by Koomen [258] and methods to analyse urban growth and sprawl using remote sensing have been developed by Bhatta. [259] The process of data interpretation can be done manually, for instance by tracing desired features, or automatically by deploying

256 Nebel and Salcedo, *Al Buraimi, A Strategic Approach towards Integrated Urban Development and Resilient Urban Management*.
257 Hansen et al., "High-Resolution Global Maps of 21st-Century Forest Cover Change," 853.
258 Koomen et al., *Modelling Land-Use Change*.
259 Bhatta, *Analysis of Urban Growth and Sprawl from Remote Sensing Data*.

Object-Based Image Analysis (OBIA) algorithms. OBIA emerged recently as an automatic way to identify feature regions, compare and validated the regions by evaluating neighbouring pixels, and finally to classify the results in aggregated land cover classes. Satellite data contains several spectral reflection bands. Specific land cover types reflect 'signature' band values that can be used to determine land cover.

OBIA has been used in moderate climates for built-up area recognition where the distinction between the built and the non-built environment is already visible in the colour spectrum of the satellite image. Furthermore, the infra-red, ultra-violet and x-ray bands of the satellite can easily detect ground humidity levels that further helps to classify the land cover. OBIA is more challenging in the case of an arid landscape like in Oman where reflective values of dusty building roofs, roads and infrastructure is almost identical to the dusty gravel environment. Von Richthofen and Langer developed a first approach to overcome the problem of similar reflective values in satellite images and to derive consistent land use classification in Oman for the Muscat Capital Area (SEE FIGURE 2). In their article the authors develop a double scale validation method that first identifies built structures at the finest resolution of 15×15 m. A second scan at a larger resolution of 90×90 m determines whether the region has a substantial built-up ratio. Only if this condition is met then the earlier fine grain detection is validated as contributing to the built-up area. Further land cover types have specific sizes (an Omani house is typically 12 × 20 m large, other buildings are larger) and have distinguishable shapes (rectangular shape for instance) that can be used to validate the type of land cover detected by spectral value. The automation allows to analyse larger areas and more scenes with constant quality. In this case six different time stamps, from 1984–2017, were analysed. A reference basemap of urbanisation was created by author and students of GUtech's Department of Urban Planning and Architectural Design (UPAD), in March 2012 and in March 2013. The maps obtained from OBIA were then checked against the manually traced maps for accuracy. The resulting urbanisation maps were consistent. The results produced by von Richthofen and Langer allowed creating an accurate temporal map of Muscat Capital Area. The overlay of these maps further allowed to visualize the rates of change from one temporal step to the other and to quantify built space, buildable reserve space and unbuildable spaces for the districts of Muscat governorate.

The maps in the following sections were produced using the open-source GIS software ‘QGIS’ 260 and the open-source remote sensing software ‘InterIMAGE’. 261 QGIS is a professional GIS software with all capacities to display, organise and compute geo-spatial information. Since data on land transformation in Oman was not available at the desired resolution, the remote-sensing strategy of OBIA was used with the programme InterIMAGE. This programme allows to automatically and intelligently interpret raster satellite image information. A semantic model of representational concepts and expected classes of objects can be created within InterIMAGE. This allows to gradually approximate the resulting land cover classes by using specialized image processing operators. Rule models further allow to explain the classification process with desired precision and consistency across the large amount of satellite data.

PARSING SATELLITE DATA

The Landsat archive satellite material is available for the region since 1984 (SEE FIGURE 25). 262 While several missions (LS 4–8) covered the area not all scenes were usable, in particular due to gaps in the Landsat 7 mission. 263 Landsat 5 satellite images were used for the 1990 time point, Landsat 7 for 2000 and Landsat 8 for all recent scenes.

Different time points in the past are necessary to describe the morphological origin and rates of change in land cover. The determination of the number of time points and their temporal distance is a compromise of availability and consistency of satellite data, required temporal resolution and expected significance of change rate. Within the scope of this dissertation the chosen time points were limited by the earliest available satellite data, from 1984, Landsat 7 data gaps and the decision to ‘sacrifice’ temporal resolution for an increased scalar analysis at the national, regional and local level. After exploring several possible time points the following years were selected: 1990, 2000, 2013 and 2017.

260 “QGIS: A Free and Open Source Geographic Information System.”
261 “InterIMAGE: An Open-Source, Knowledge-Based Framework for Automatic Image Interpretation.”
262 “Landsat.”
263 U.S. Geological Survey, “Landsat Known Issues.”

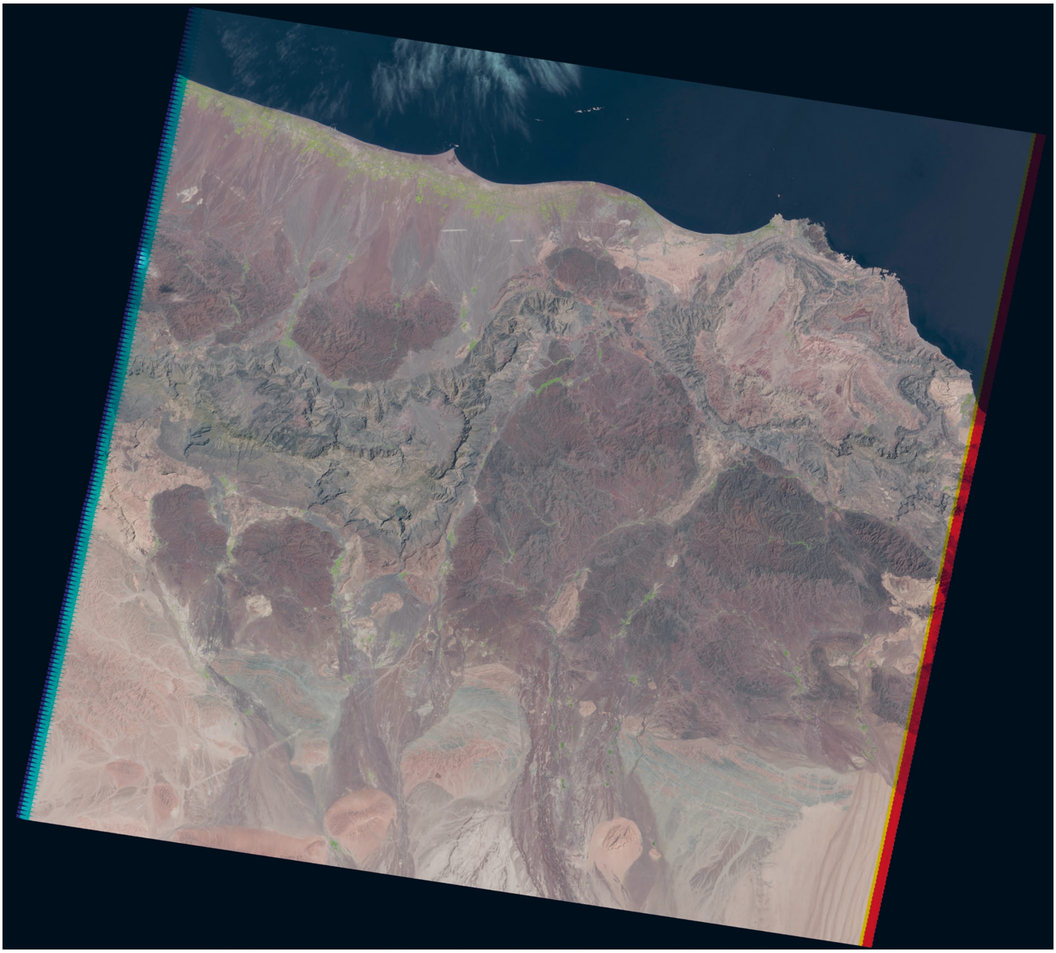


FIGURE 25
Landsat 7 Satellite Images for Muscat Capital Area. (U.S. Geological Survey, 2017)

The scales of observation range from national covering of all of Oman to regional focussing on Muscat Capital Area, Nizwa in the Omani Interior and Salalah in the south, and 18 local samples within these regions. The location of regional areas corresponds to the main urbanisation cores of Oman. The local samples within these were selected because of the indicative features of being located at various points of the urbanisation: centre, outer neighbourhoods, rural-urban interface and rural settings. The national observation level covers the whole country. The size of the regional levels is 40×40 km except for the case of Muscat Capital Area, where it is 50×100 km. The size of the 18 local samples is 2×2 km. The consistent scale allows for a comparative analysis of the samples (SEE FIGURE 26).

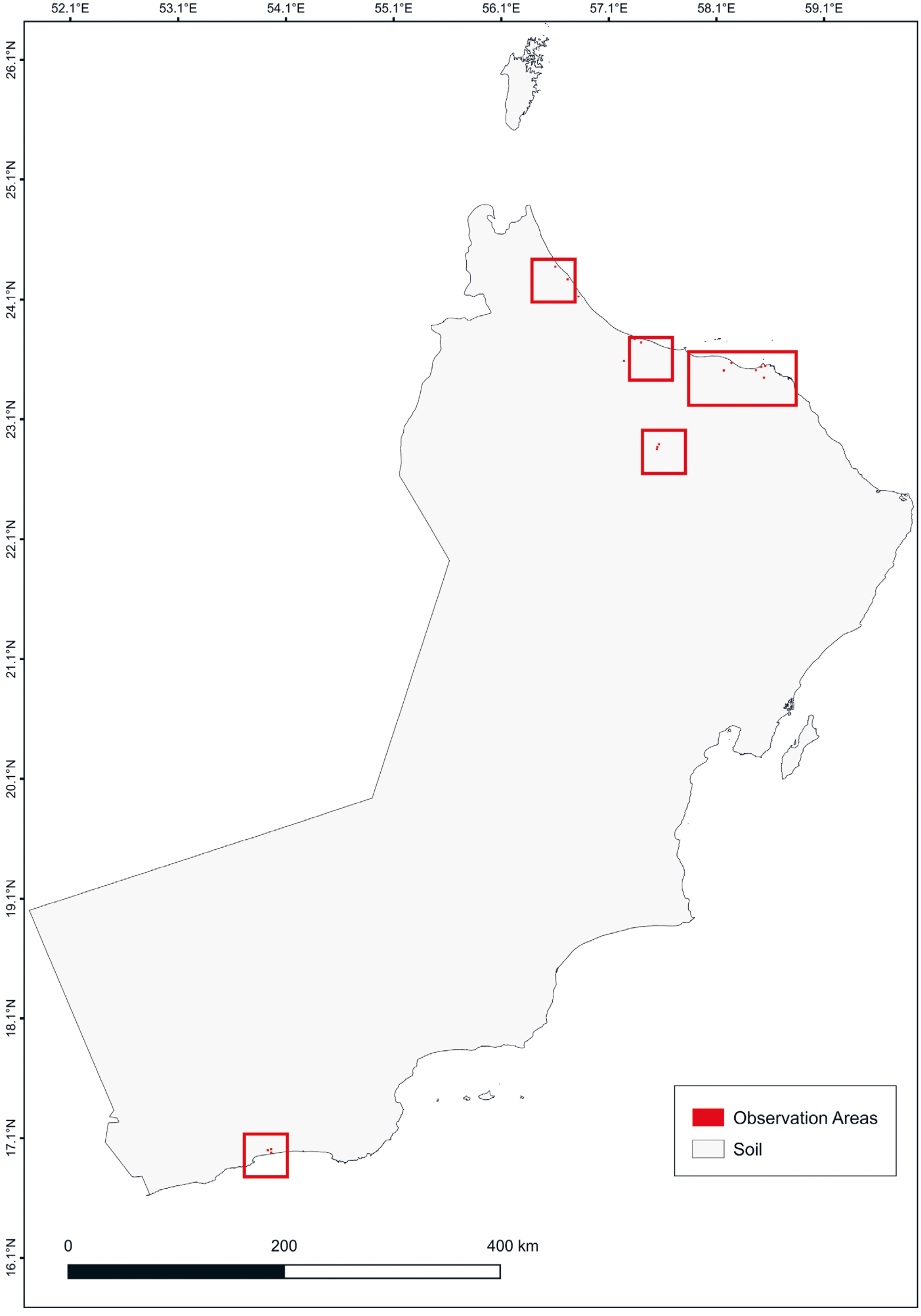


FIGURE 26
Map of Oman with regional and local observation areas.

Landsat satellite images of Oman were first pre-processed by applying atmospheric correction to remove atmospheric effects such as clouds, and by retrieving the surface reflectance and pan-sharpening merging coloured 30-m resolution and panchromatic 15 m resolution files using the Semi-Automatic Classification Plugin (SCP) tool available in QGIS. 264 The final resolution of the satellite images was then 15 m. A stacked raster file was then created using pan-sharpened bands 2–7 with the band set tool in SCP. An reg, green and blue (RBG) colour setting of band 3–2–1 was applied in the layer style panel to obtain a composite colour image.

AUTOMATIC CLASSIFICATION

This dissertation focusses two land cover classes: Built-up space and vegetation space of Oman. InterIMAGE conceptualises automatic image interpretation as a semantic net. This net divides the overall image data set into a desired tree of sub-sets. Each node in this semantic net links a single 'parent' set to one or more 'child' sets (SEE TABLE 4). Input data can be satellite images, GIS and DEM. The semantic net can be tested with top-down operators following a hypothesis and with bottom-up operators following several different instances. Both confirm or reject and eventually resolve spatial conflicts. As a result, InterIMAGE creates a symbolic representation of the sub-sets and layered thematic maps. 265

The semantic model constructed in InterIMAGE uses the following semantic net (SEE TABLE 4):

SATELLITE IMAGE:
– Buildings
– Vegetation
– Soil 1
– Soil 2
– Soil 3
– Water
– Unclassified

TABLE 4
Semantic model of land-classification constructed in InterIMAGE.

264 Congedo, "Semi-Automatic Classification Plugin Documentation."
265 "InterIMAGE 1.41 – User Guide," 2.

The classes for buildings and vegetation were obtained by selecting typical ROIs for training of the software using the bottom-up approach. For both cases the recognition of soil types was done iteratively, hence the classification of semantic distinction of Soil 1, Soil 2, Soil 3. These nested soil classes aim to incrementally detect urbanised or agricultural land 'hidden' by misclassification. Furthermore, the land covers Water and Unclassified were introduced with the aim to manually re-classify spaces that could not be remote sensed automatically.

Each raster image was classified using the Semi-Automatic Classification Plugin 5.3.6.1 into multiple land cover classes. Sample Regions Of Interest (ROIs) were first selected by visually identifying cells of land cover features (e.g. buildings, vegetation). The training of the semantic net served to determine top-down operators such as spectral band parameters to identify the desired land covers. In a next step the sample ROIs were tested using bottom-up operators: distance-similarity between pixels (0.01), minimum area of ROI (5), maximum area of ROI (100). Training sample cells were saved to a training input file for each desired land cover. Raster images with less than 5 buildings or 5 plots of vegetation on land counted were classified as 'Soil' (SEE FIGURE 27).

FIGURE 27
Original satellite image with ROIs for built space and vegetation.

In the following, the parameters for detection of land cover classes 'Soil' were increased until non-buildings and non-vegetation cells were eliminated from their respective building and vegetation classes. Each raster image was then optically checked for classification accuracy and compared to the study conducted by von Richthofen and Langer (2015), as well as to manually traced regions. Contiguous areas of cells that were unsuccessfully classified were reassigned raster values using the 'Edit Raster' tool found in the SCP. The classification tool was then run with assigned raster values of 1 for Buildings and 2 for Vegetation, with values saved in a raster TIF format file (SEE FIGURE 28).

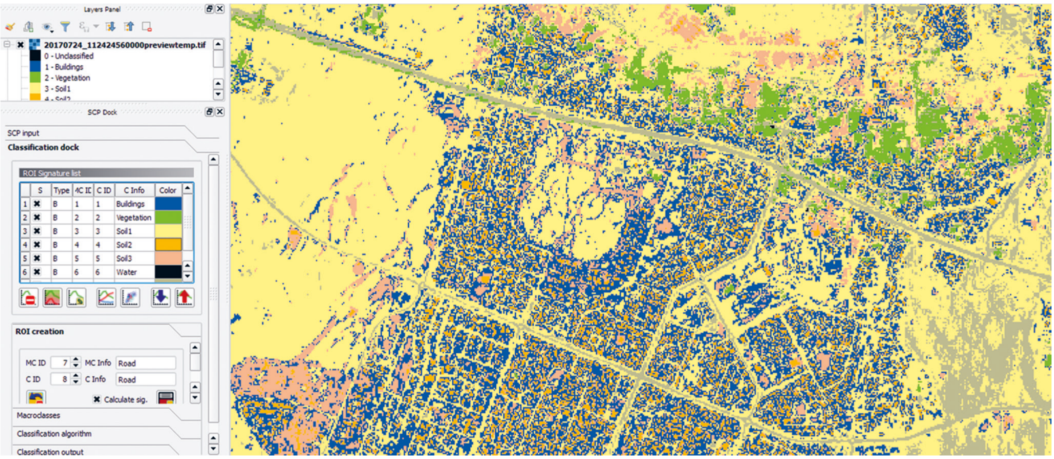


FIGURE 28
Incremental soil classification process using InterIMAGE.

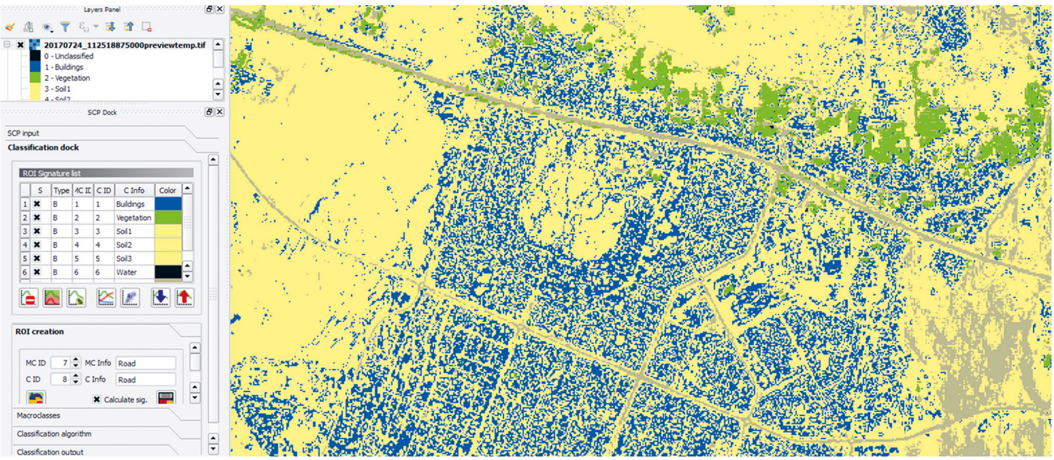


FIGURE 29
Final land use cover classes built-up space and vegetation.

All raster images were then mosaïcked using in QGIS, using a mosaïc-type operator of 'minimum', whereas the output cell value of the overlapping areas will be the minimum value of the overlapping cells with a no-background value of '0' and a no-data value of '0'. The mosaïc was then clipped to the administrative boundary of Oman and both the building and vegetation layers were then separately exported as map layers (SEE FIGURE 29).

ADDITIONAL GIS LAYERS

Other GIS sources used include Shuttle Radar Topographic Mission (SRTM) at the resolution of 90 m and 30 m per tile. 266 This global elevation dataset was used to generate contour lines, watershed, flood areas and elevation profiles. Open Street Map offers an up-to-date road network with detailed attributes that allow to calculate road surface areas by creating buffer zones. Since this data is constantly updated it can only reflect the present situation and not be used for historic time points 267. Various data sets such as coarse resolution land cover, hydrology and geology datasets found on the U.S. Geological Survey (USGS) were also used to enrich and validate the data. The Global Administrative Areas (GADM) offer a recognized dataset on boundaries.

MAP PRODUCTION

The map production was first carried out at national scale as described above. The same method was then applied to the regional and local scales. The map layers for built-up space and vegetation space were combined in QGIS.

Each built-up space and vegetation space layer was then combined to juxtapose the extent of these land cover zones. The time points 2017, 2013, 2000 and 1990 were used to the create overlays and describe the land use change from one time-point to the next: 1990–2000; 2000–2013 and 2013–2017. As such, they allow to quantify the rates of change from one time point to another for all map scales. The time point maps can also be overlaid to produce a sequence of urban expansion from 1990–2017 (SEE FIGURE 30).

266 "30-Meter SRTM Tile Downloader."
267 "OpenStreetMap."

FIGURE 30

Sequence of urban expansion of Muscat Capital Area from 1990–2017.

MAP ANALYSIS

Next to the visual interpretation of the resulting changes in land used cover morphology the urbanised areas were counted for statistical analysis. This count enables to establish the spatial diversity index as described later. This index is based on a relative comparison of land cover mapping classes. The resulting diversity index value is thus independent of measuring errors, as the scale of the error applies universally.

The maps were also computed and quantified in absolute terms in total square kilometres and percentage of the respective observation scene. The calculation follows this rule:

land cover area 'X':

> Pixel count in scene: total number of pixels T and number of pixels of land cover X
>
> Area = number of pixels X * pixel length in m * pixel height in m = x m²
> % of Oman covered by land cover area

For example: land cover area built-up space in Oman:

> Pixel count in scene: total number of pixels: 1.372.675.556 and number of pixels of land cover area built-up space: 1.996.872
>
> Area = 1.996.872 * 15 m * 15 m = 449.296.200 m²
>
> % of Oman covered by land cover area built-up space = 1,45 % of the total area

The values calculated are absolute values in terms of pixel counts, yet they should not be taken for face value as these figures contain error margins. A pixel identified represents a value of 225 m² of built-up space and ignores the possibility of unbuilt space in between.

ACCURACY ASSESSMENT FOR REMOTE SENSING

The accuracy assessment for remote-sensed image classification was done in QGIS using the Semi-Automatic Classification Plugin (SCP) 3. [268] First, a set of random points was created. Those points were manually classified by ground truth and then compare to the remote-sensed raster data in a confusion matrix. The Equalized Stratified Random sampling strategy was used to generate a set of accuracy points for agricultural and residential land cover. Three land cover classes were considered: Agricultural, built-up and desert. The error matrix computed an overall accuracy of 83.4%. The remote-sensed image classification is thus relatively accurate on a global scale, but the error needs to be considered when interpreting the result.

SPATIAL DIVERSITY INDEX

The literature on biodiversity measurement, patterns and distribution uses two key measures: The richness of species as their absolute numeric value, and the diversity as a relative value. The richness represents the count of a distinct item in a sample area: *"Species richness is the number of species of a particular taxon (e.g., birds or grasses) or life form (e.g., trees or plankton) that characterises a particular biological community, habitat, or ecosystem type."* [269] Diversity is most commonly calculated with Shannon's diversity and this calculation will be used here. *"Diversity indices are mathematical functions that combine richness and evenness in a single measure, although usually not explicitly. Although there are many others, the most commonly used diversity indices in ecology are Shannon diversity, Simpson diversity, and Fisher's."* [270] Shannon's diversity further distinguishes α,β,γ densities to describe species diversity α, differentiation diversity β and regional diversity γ of species. Since we are interested in the accumulated space of a sample map computed for the accumulated data we will use the species diversity α.

The spatial diversity index has been designed for this thesis. It is based on insights from biodiversity measures and geared towards spatial features that can be detected with remote sensing technologies. We will now need to define what distinguishes our

268 Congedo, "Semi-Automatic Classification Plugin Documentation."
269 Colwell, "Biodiversity," 258.
270 Colwell, 260.

space species and why. Remote sensing enables to detect functional land cover classes (vegetation and built-up areas) as well as their spatial geometric properties. These map features can be automatically computed to feed into the individual diversity indices. This dissertation focusses on urbanised areas and agricultural land as two land cover classes, each forming a sub-index. Together these indices are aggregated to form the 'species of space' diversity index. Space species have unique features and distinct categories, just as biological species have. The dimensions included to differentiate these species just depends on how thorough the analysis is meant to be. The dimensions can easily be expanded if necessary. We will include the size, edge length and compactness to form the space species:

- **Size**: Each patch in the sample area has a size that is significant for the contribution to the spatial system. The smallest patch size is defined by the minimum pixel resolution of the sample data, in this case a 15×15 m square of 225 m² area. The distribution of area sizes within a feature set can be shown in a histogram per map. The size is an absolute value measured in m².
- **Edge Length**: The edge length or periphery is computed by the sum of the patch length. The smallest patch is defined by the minimum pixel resolution of the sample data, in this case a 15×15 m square with an edge length of 4×15 m = 60 m length. The edge length increases with the patch area, but more compact patches will have a smaller patch area to patch length ratio which is defined as compactness. The edge length is an absolute value measured in m.
- **Compactness**: The compactness is the ratio of patch area to patch length. The geometric property of 'compactness' of feature classes can be inferred by comparing the area to the periphery of a feature. The most compact two-dimensional feature would be a perfect circle where the compactness would equal the number Π. This measure is unit-less. Since we evaluate square pixels of 15×15 m size, the most compact value is 225 m² (area) divided by 60 m (periphery) = 3.75. Less compact, more scattered features will have a higher sub-index.

SPACE SPECIES

Each sub-index has a range: size (small to large), edge length (short to long), compactness (compact to scattered). The resulting eight theoretical space species are shown in this matrix. The species can be named according to their combination of small or large; short or long; compact or scattered into (SEE TABLE 5): CSS; CSL; CLS; CLL; SSS; SSL; SLS; SLL.

COMPACT	SMALL	LARGE
Short	Compact / Small / Short	Compact / Large / Short
Long	Compact / Small / Long	Compact / Large / Long

SCATTERED	SMALL	LARGE
Short	Scattered / Small / Short	Scattered / Large / Short
Long	Scattered / Small / Long	Scattered / Large / Long

TABLE 5
Matrix of possible space species.

INDEX CALCULATION

The index is now calculated by applying Shannon's diversity index to the space species found for each feature class (vegetation and built-up space). Shannon's diversity index can be represented as follows:

$$H' = -\sum p_i \, lnp_i$$

In ecology, or for our case in spatial settings, *pi* is the proportion of samples belonging to the *i*th category to be evaluated. 271 The results can be interpreted in this way: *"When all types in the dataset of interest are equally common, all pi values equal 1/R, and the Shannon index hence takes the value ln(R). The more unequal the abundance of the types, the larger the weighted geometric mean of the pi values, and the smaller the corresponding Shannon entropy. If practically all abundance is concentrated to one type, and the other types are very rare (even if there are many of them), the Shannon entropy approaches zero. When there is only one type in the dataset, the Shannon entropy exactly equals zero (there is no uncertainty in predicting the type of the next randomly chosen entity)."* 272

INTERPRETATION AND LIMITATIONS

The interpretation of the results follows the diversity discussion of any Shannon diversity: *"Shannon diversity increases as richness increases, for a given pattern of evenness, and increases as evenness increases, for a given richness."* 273

The index itself is based on purely geometrical and spatial data. It offers a quantitative score for each sample area. The significance of the index derives from associated attributes that have been

271 Hill, "Diversity and Evenness."
272 Wikipedia, "Difersity Index."
273 Colwell, "Biodiversity," 260.

identified through empirical studies by the author on relevant cases. The index is considered significant because it identifies agricultural land as the most vulnerable land class in Oman because of irrigability, irreversibility of land use, encroachment of built environment, economic pressure, etc. Large parts of agriculture in Oman are not industrialised. Oasis agriculture in particular contributes to bio-diversity in Oman. 274 Bio-diversity increases over larger connected areas, yet edges and interfaces between habitats offer important bio-diversity hot-spots. 275 Larger clusters of agricultural have higher spatial diversity values because of multiple synergetic effects related to efficient use of water, micro-climatic effects, long-term sustainability of land use, cultural, social and economic aspects, etc. Larger and connected land use clusters are better than fragmentation for the same reasons. The preservation of larger and connected agricultural areas is a resilient strategy that protects land use conversion of smaller areas are subject to incrimination of clandestine conversion of 'waiting land' to buildable land. The index is a comparative measure across all sample areas for rapid assessment. The map feature errors have been discussed in the mapping chapter. Since the error values are even we can say that they don't bias the formation of the index but cannot, for instance, be used as absolute values of available land use areas.

PARAMETRIC URBAN MODELLING

Parametric urban modelling serves to bridge the gap between the geographic scale of remote sensing and the physical scale of urban design. The parametric urban model provides additional three-dimensional information when using otherwise two-dimensional maps. Parametric models are driven by rules that react on the underlying remote-sensed maps. The rules are designed with specific urban design targets in mind. Changes in maps act as new inputs to the rules that then change the resulting form and thus offer an immediate visual and quantitative data feedback. They allow testing urban design-specific aspects such as densities, typologies, urban form in three dimensions and to visualising the results. This method supports rapid urban prototyping and forecasting of alternative urbanisation models. The models critique the present urban design approach in Oman that has been analysed in exemplary

274 Gangler, "Oasis Settlement Structures/Oman."
275 Fischer, Lindenmayer, and Hobbs, "IV.2 Landscape Pattern and Biodiversity."

case studies. They also allow to evaluate future urban development scenarios and in particular the interlinking aspects of housing and agriculture in particular. They become planning models and evaluation tools at the same time.

SHAPE GRAMMARS AND RULE-BASED URBAN DESIGN

Parametric urban design builds upon two fundamental concepts. The 'Pattern Language' by Alexander [276] and the 'Shape Grammars' by Stiny and Gips. [277] The 'Pattern Language', developed in the 1960s, is the attempt to represent urban phenomena (patterns) as semantic systems (language). Alexander draws the patterns from traditional architectural design observation. Urban patterns or elements assist in developing an operational catalogue for urban design: *"An urban element combines, or knots together, different aspects of these themes in the city. The term relates to concepts of type and genre in urban design, and heuristic approaches to knowledge formation (or rules of thumb). Elements are typical features of good city form that can range in scale from the texture of a pavement, a building entrance, to shop front, to pocket park, to plaza and street, to neighbourhood and precinct."* [278]

This concept has been debated here mainly because of the inherent and poorly understood complexity of urban phenomena on the one hand and the incomplete comprehension of design processes and designcognition on the other, that resist a reduction to a discreet set of patterns and rules. Yet the idea of pattern language in urban design has seen a renaissance, as computational power and knowledge about both urban complexity and design cognition rises.

The 'Shape Grammars' developed by Stiny and Gips at the same time as Alexander's pattern language use geometric shapes as the base for rule based transformation. [279] This principle is applicable to mathematics, arts and to geometry in general, thus for all spatial design practices that use geometry to represent form. Stiny and Gips describe how the transformation process is governed by rules. These rules will produce more shapes to which more rules can be applied, etc. In following this logic any complex form

276 Alexander, Ishikawa, and Silverstein, *A Pattern Language*.
277 Stiny and Gips, "Shape Grammars and the Generative Specification of Painting and Sculpture."
278 von Richthofen, *Urban Elements – Advanced Studies in Urban Design*, 174.
279 Stiny and Gips, "Shape Grammars and the Generative Specification of Painting and Sculpture."

can be built-up by sets of shapes and rules. Together they form the 'grammar'. Because of this mathematical logic, shape grammars can be implemented in computational design tools and facilitate the generative design processes.

The concepts of pattern language and shape grammars have been applied by the author in various urban design courses and studios. 280 Koneiva describes how to develop parametric design proposals for emerging urban settings in Ethiopia and Singapore. This design-driven approach deliberately reduces the complexity of modelling urban phenomena in favour of visualising design proposal; such attempts are being proposed by König and Bauriedel, Batty, Bettencourt, Zünd. 281 The aim of the urban design model proposed here is not to simulate future urban developments. A simulation requires knowledge about agents whose behaviour can be modelled to study emergent patterns. This can be done with cellular automata and agent-based models, for instance to model informal urban growth under rapid urbanisation. 282 They describe the state of the art of parametric urban design as follows:

> "Parametric design tools accept variable input data, establish mathematical relationships and produce further data, including geometric information. 283 With advances in computing power and the growing availability of data, parametric systems can now be employed to deal with complex urban phenomena on a multi-scalar and multi-dimensional level. In comparison to conventional design methods, parametric urban design uses rule sets as the basis for the configuration of 3D urban models. The advantage of this is that it enables the exploration of a wide range of alternative solutions by changing the parameters of the logical relationship, whereas for traditional methods, designers usually only consider a relatively limited number of alternative solutions. 284 Another advantage is that designers can change and modify their own rule-based models

280 von Richthofen, *Urban Elements – Advanced Studies in Urban Design*; von Richthofen et al., "The 'Urban Elements' Method for Teaching Parametric Urban Design to Professionals"; Konieva et al., "Parametric Assistance for Complex Urban Planning Processes."
281 Koenig and Bauriedel, "Computergenerierte Strukturformen v.01"; Batty, "Urban Modeling"; Batty, "A Theory of City Size"; Bettencourt, "The Kind of Problem a City Is"; Zünd, "A Meso-Scale Framework to Support Urban Planning."
282 Hill and Lindner, "Modelling Informal Urban Growth under Rapid Urbanisation."
283 Steinø and Veirum, "A Parametric Approach to Urban Design – Tentative Formulations of a Methodology."
284 Woodbury, *Elements of Parametric Design*.

at any stage of the design process so that it can be kept open and flexible, because all procedures, activities, and relations in parametric design are clearly defined. 285 In short, parametric urban design can be used to model alternative scenarios, visualisations and quantifications all in one – a key advantage over conventional design methods. A parametric urban design is thus agile to changing input constraints and offers flexible solutions that can be re-computed depending on stakeholder perspective. 286

The translation of rule-based principles into geometric form originates in so-called 'shape grammars'. 287 The implementation of generic urban design models with shape grammars has been explored by Beirão, Karakiewicz and Kvan. 288 Beirão, Duarte, and Stouffs also identified specific shape grammars necessary for urban design. 289 Multiple technical challenges in identifying and solving particular urban design aspects have been addressed by Koltsova, 290 as well as by Bielik. 291 Architectural building information models (BIM) have been expanded to cater for urban design tasks and some approaches offer systematic tool collections enabling urban designers to work on urban design projects. 292 These also accommodate the scalar dimensions of urban design by 'nesting' smaller scalar units (houses or neighbourhoods) into larger ones (districts or regions). 293 Some software packages now also offer 'shape grammars', for example, the commercial software 'CityEngine' released in 2008, solves generic urban problems by means of the shape grammar logic." 294

285 Oxman and Gu, "Theories and Models of Parametric Design Thinking."
286 Barrios Hernandez, "Thinking Parametric Design."
287 Stiny and Gips, "Shape Grammars and the Generative Specification of Painting and Sculpture."; Stiny, *Shape*.
288 Beirão et al., "Implementing a Generative Urban Design Model"; Karakiewicz and Kvan, "Diagrams as Parametric Systems in Urban Design – Parametric Systems Applied to Conceptual Design."
289 Beirão, Duarte, and Stouffs, "Creating Specific Grammars with Generic Grammars: Towards Flexible Urban Design."
290 Koltsova et al., "Parametric Tools for Conceptual Design-Support at the Pedestrian Urban Scale."
291 Bielik et al., "Parametric Urban Patterns."
292 Kim, Clayton, and Yan, "Parameterize Urban Design Codes with BIM and Object-Oriented Programming."
293 Zünd, "A Meso-Scale Framework to Support Urban Planning."
294 von Richthofen et al., "The 'Urban Elements' Method for Teaching Parametric Urban Design to Professionals."

EXCURSUS: AGENT-BASED MODEL OF RESIDENTIAL SETTLEMENT BEHAVIOUR

The co-authors have developed an agent-based model to examine the particular consequences of the Omani real estate market: *"The simulation describes the agents and their motivation. It is calibrated with a real-estate price index compiled for Muscat Capital Area for the first time. The simulation allows discussion of four scenarios: Status quo, negative, positive and combined land management measures. The status quo scenario reveals that the original intention of the land allocation program as part of the welfare system in Oman is not attained."* 295 The research question was to find how the actual residential development process unfolds in time and in space; if the land allocation lottery would lead to efficient and complete residential settlement (e.g. no more vacant land left); if infrastructure provision affects the process; and to gain insights on the real estate market and land speculation in Oman. The hypothesis was that the land allocation system by lottery, albeit a welfare idea, would not lead to fair and equal wealth distribution nor to efficient land use. The agent-based model identified the following agents and their varied behaviour (SEE TABLE 6):

Fast Sellers (Fn): in need of instant cash (e.g. to buy a car)	a	sell	don't build	now
Pioneer Movers (Pn) in need of immediate home (e.g. family founder)	b	keep	build	now
Neighbourhood-driven for own use (Nn)	c	keep	build	later
Infrastructure-driven for own use (In)	d	keep	build	later
Aggregate speculation for rent/sale (An)	e	keep/sell	build/don't build	later
Accumulate speculation for rent/sale (Cn)	f	keep/sell	build/don't build	later

TABLE 6

Overview of the motivations/desires of owners, their sales and construction strategies as well as their urgency to carry out their strategies. 296

295 Heim et al., "On the Process and Economics of Land Settlement in Oman: Mathematical Modeling and Reasoning in Urban Planning and Design"; Heim et al., "Land-Allocation and Clan-Formation in Modern Residential Developments in Oman."

296 Heim et al., "On the Process and Economics of Land Settlement in Oman: Mathematical Modeling and Reasoning in Urban Planning and Design."

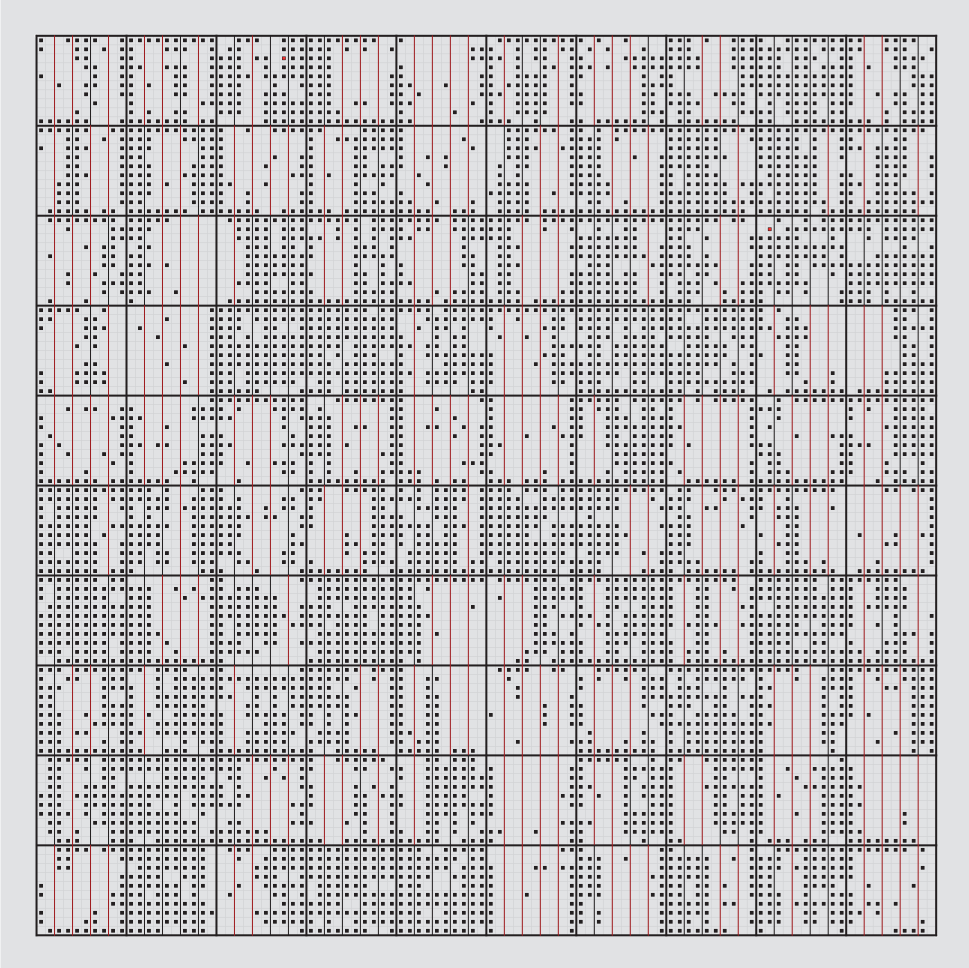


FIGURE 31
Simulation of the settlement process: early phases showing established and new settlers (agents) based on Heim. 297

The simulation was conducted on a grid size of 100×100 cells and ran for 1000 iterations (SEE FIGURE 31). It allowed to trace the trade behaviour of each agent and to play out urban management scenarios including incentives and taxation. The agent-based model was further refined to include tribal affiliation and to test the formation of clan-clusters. 298 Insights from both agent-based models have been fed into the urban design process of this thesis.

297 Heim et al.
298 Heim et al., "Land-Allocation and Clan-Formation in Modern Residential Developments in Oman."

ANALYSIS AND CRITIQUE OF THE STATUS QUO

The parametric urban model proposed here – its input parameters and rules logic – is developed based on case studies in Oman. This empirical research allows to distil key parameters for design. Distilling urban design principles needs to be done strategically. The base-line model follows the status quo. The explicit logic of parametric models also reveals shortcomings of the current urban design and serves as critique. The alternative model aims to overcome the shortcomings identified. The resulting models are then compared and evaluated. The research of the status quo focuses on residential neighbourhoods in Muscat and the rural-urban interface to distil parameters for an alternative integrated residential and agricultural development.

The study of the prevailing planning standards and building code in Oman has been done by translating the main code elements from textual into graphic form. The 'Physical Planning Standards' developed by Atkins describe the spatial organisation of the main functional elements of the Omani cities, [299] whereas the 'Building Regulations' regulate the buildable envelopes within the plot boundaries. [300] Together with the functional zoning plan developed by Weidleplan these documents shape the structure of urban morphology of Oman in the 1990s. [301] As the visual translation of the 'Building Regulations' shows, all acceptable building typologies resort back to a free-standing building. Its footprint and height are governed by the proposed use. Setback requirements from the plot edges prohibit a continuous building typology, such as a row-house or mat-typology. The self-standing buildings are thus exposed to solar radiation from all sides. The setback requirements are not so generous as to mandate interstitial spaces between buildings that could actually be used productively either as agricultural or as common space. They are in practice not even usable as park cars and are usually waste spaces. The houses are exposed to all sides, yet there is a cultural need for privacy. This is achieved by a perimeter wall around the building that further segregates the private and public spaces. The space wasted by this single-villa typology is significant. It amounts to 50% of the plot area for a standard 600 m² plot and even more on the neighbourhood level if all residual spaces in between plots, massive roads and curbside spaces are counted. Each plot is thus not used

299 Atkins Int., "Physical Planning Standards."
300 Muscat Municipality, "Building Regulation for Muscat – The Sultanate of Oman."
301 Weidleplan, "Muscat Area Structure Plan Phase 3 Final Report."

efficiently and each neighbourhood requires more and more space, which in return demands more and more infrastructure – a classic example of urban sprawl. The conjuncture of 'Physical Planning Standards' and 'Building Regulations' does not produce meaningful urban spaces: *"Critique aimed towards rigid two-dimensional 'guideline + zoning-map' concepts that further complemented the plan had already emerged in Europe by the late 1980s. The US developed a so-called 'form-based-code' in response to it by the 1990s."* (Cummings and von Richthofen 2017, 260)

> *"To foster resource-efficient land use we recommend reconsidering plot sizes and set-backs, street widths, and physical densities towards a more compact urbanisation. Efficient land use also implies the priority to develop empty plots within an already built-up context. We recommend reconsidering the presently practiced zoning policies that favour a separation of functions (residential, commercial, administrative, industrial, or recreational use) and considerably contribute to forced mobility and to increasing urban sprawl. We recommend mixed land use development wherever feasible in order to reduce distances and to foster walkable neighbourhoods."* 302

Finally, the 'Building Regulations' don't specify any energy-efficient building types and fail to address the sustainability aspects altogether (SEE FIGURE 32).

In order to describe the status quo of residential development in Oman better, we need to sample residential developments in several locations across Muscat Capital Area that represent the urban expansion. Each sample area is examined at a 1×1km square. The locations chosen for the sampling are:

- Al Khuwair, Muscat Municipality, planned urban expansion – ca. 1995–2005
- Al Khoudh, Muscat Municipality, planned urban expansion – ca. 2006-ongoing,
- Al Mouj 'The Wave', integrated tourism project, Majid Al Futtain Group – 2006-ongoing
- Fanja, Bid Bid, rural-urban transformation – ca. 1995-ongoing

302 Nebel and von Richthofen, "Urban Sustainability in the Omani Context," 254.

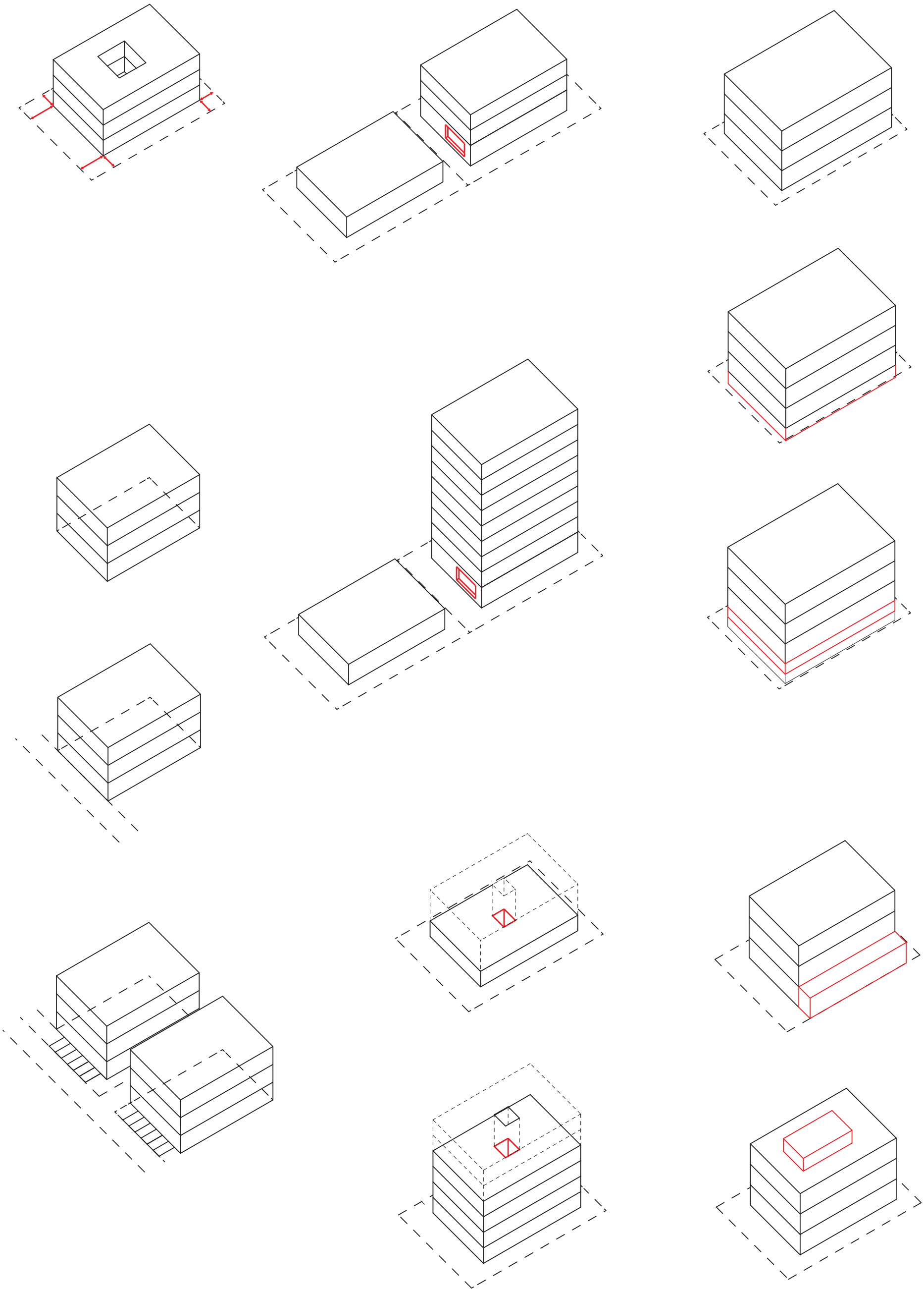


FIGURE 32
Visual catalogue of prevailing building codes for Muscat Capital Area that favour self-standing buildings and require set-back distances based on von Richthofen.
303

303 von Richthofen, "Modelling Low-Rise High-Density Neighbourhoods in Oman," 196.

Each sample area is mapped and quantitatively examined to draw basic dates and aggregated ratios for comparison purposes: *"to establish a sustainability profile compiling relevant numbers (plots, inhabitants, cars, etc.), lengths (road length), areas (open, covered, green spaces, building footprints, circulation areas, etc.) and ratios (floor area ratios, built-up area ratios, parking area ratios, circulation length ratios, etc.)."* 304 The remaining area outside of building footprints, green areas and roads forms the majority of the space in all the samples. This area is residual space formed by the prevailing urban regulations (see remaining white area in the following maps). The problematic 'waste' of space in Oman as a result of sprawl in both urban and rural settings has been address by Nebel and von Richthofen. 305 The focus in the analytical maps and quantification is thus on the relation of particular areas to the total observation area of 1×1 km.

The Al Khuwair sample in Muscat Municipality was planned as mixed use urban expansion from ca. 1995–2005 (SEE FIGURE 33). It is located next to a major highway. A nested system of roads and service alleys structure the site. The building plots differ from the standard 20×30 m plots as they are more elongated. Their orientation is in a 60° angle north. This orientation has no environmental or contextual significance. While the buildings stand close to each other forming rows, they are still detached with minimal setbacks to the sides and more substantial setbacks to the front and back. The result could be described as fishbone grid. Due to the relative age of this neighbourhood some signs of maturity and transformation are visible. Adaptation of buildings lead to mixed use and diversity in spaces. Some informal public space is available supporting a minimum of social and economic activities. The relative density and complete development speaks for this neighbourhood. The total sealed area is 39.9%, while the total green area is 10.5% for this sample (SEE FIGURE 34).

304 von Richthofen, 199.
305 Nebel and von Richthofen, "Urban Sustainability in the Omani Context."

FIGURE 33

Graphic analysis of neighbourhoods in Muscat Municipality in 1×1km sample: Muscat – Al Khuwair 2013.

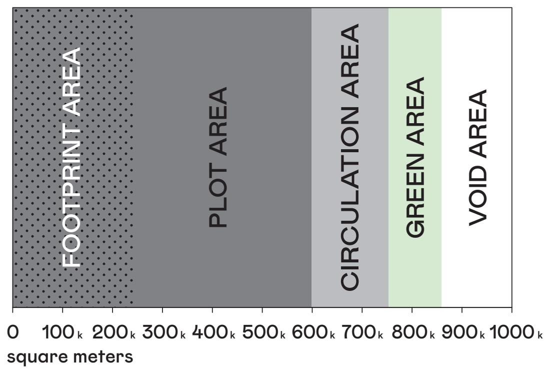


FIGURE 34

Quantitative comparison of analysed areas, for Muscat – Al Khuwair, 2013.

AL KHOUDH

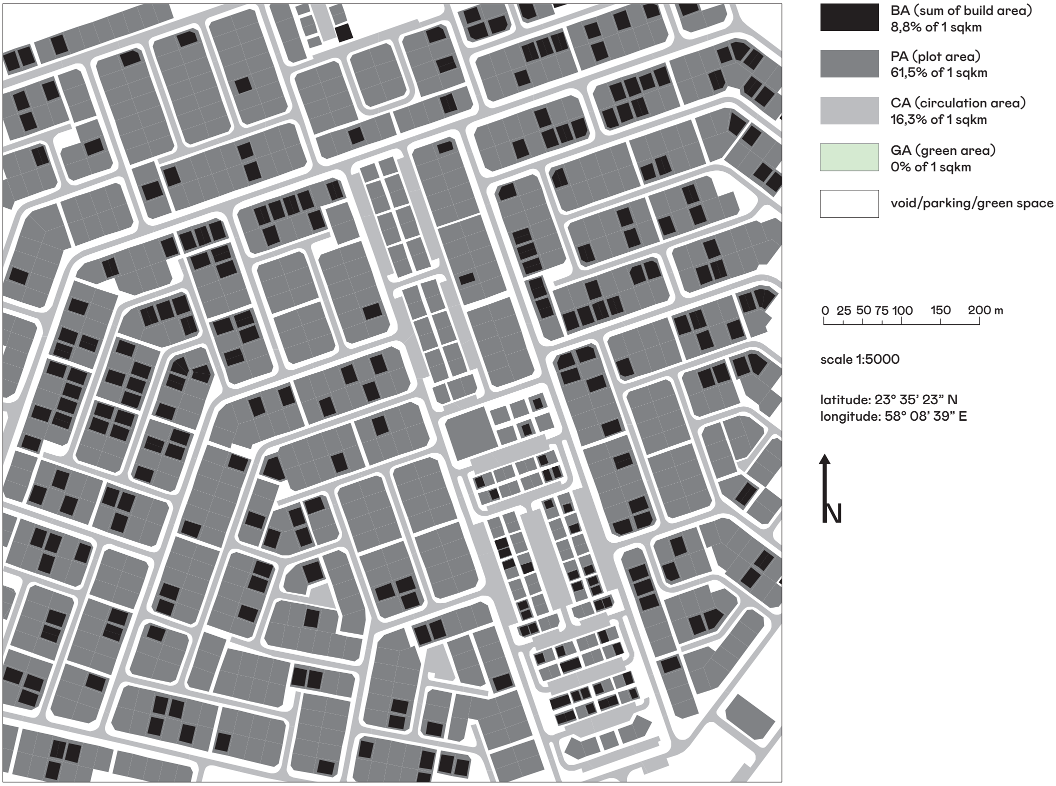


FIGURE 35

Graphic analysis of neighbourhoods in Muscat Municipality in 1×1 km sample: Muscat – Al Khoud, 2013.

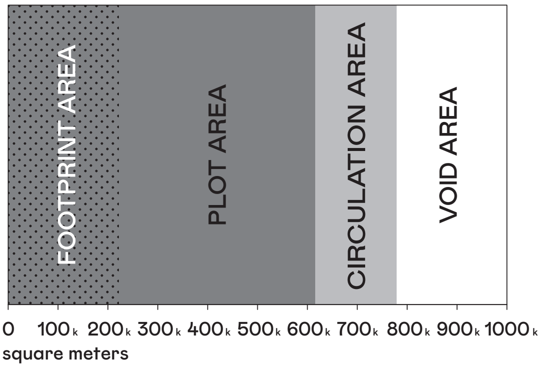


FIGURE 36

Quantitative comparison of analysed areas for Muscat – Al Khoud.

FIGURE 37

Graphic analysis of neighbourhoods in Muscat Municipality in 1×1 km sample: Muscat – Al Mouj, 'The Wave', Integrated Tourism Complex, 2013.

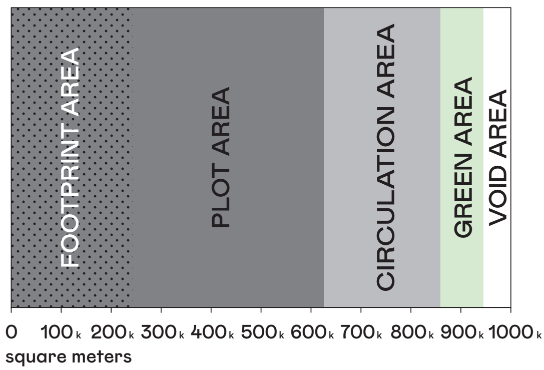


FIGURE 38

Quantitative comparison of analysed areas for Al Mouj, 'The Wave', 2013.

FANJA

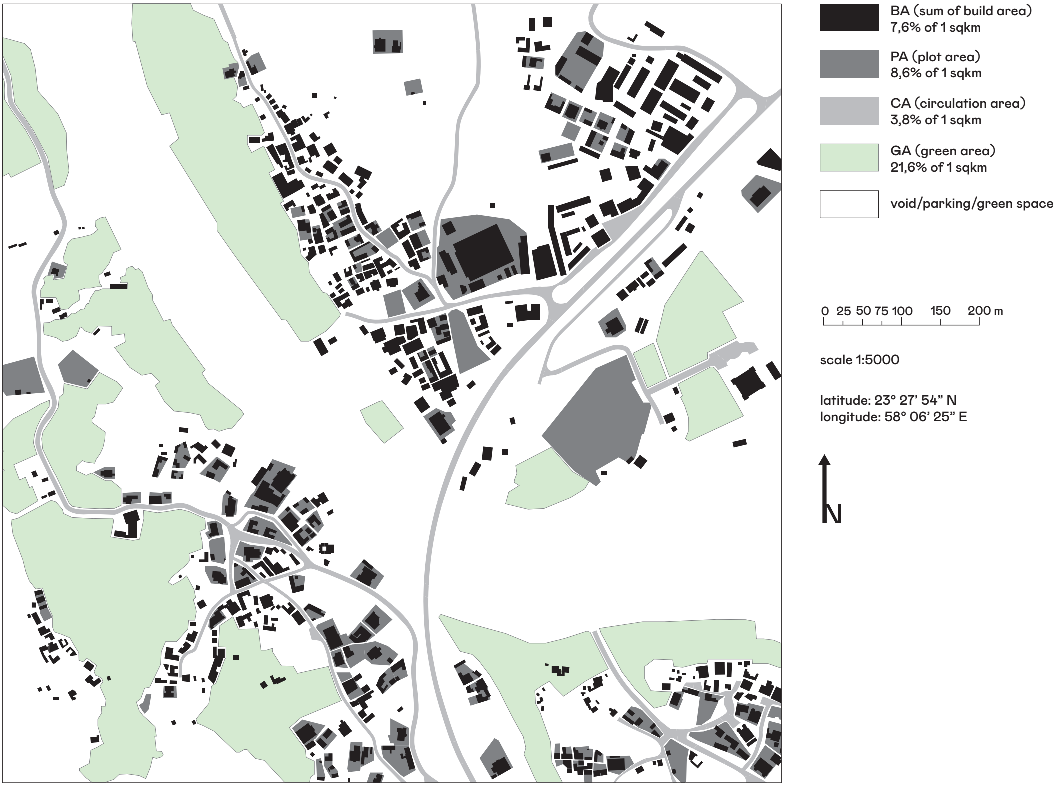


FIGURE 39

Graphic analysis of neighbourhoods on the outskirts of Muscat in 1×1km sample: Bid Bid – Fanja, 2013.

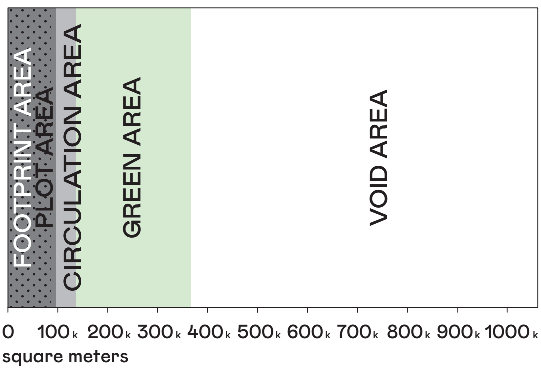


FIGURE 40

Quantitative comparison of analysed areas for Bid Bid – Fanja, 2013.

MUSCAT

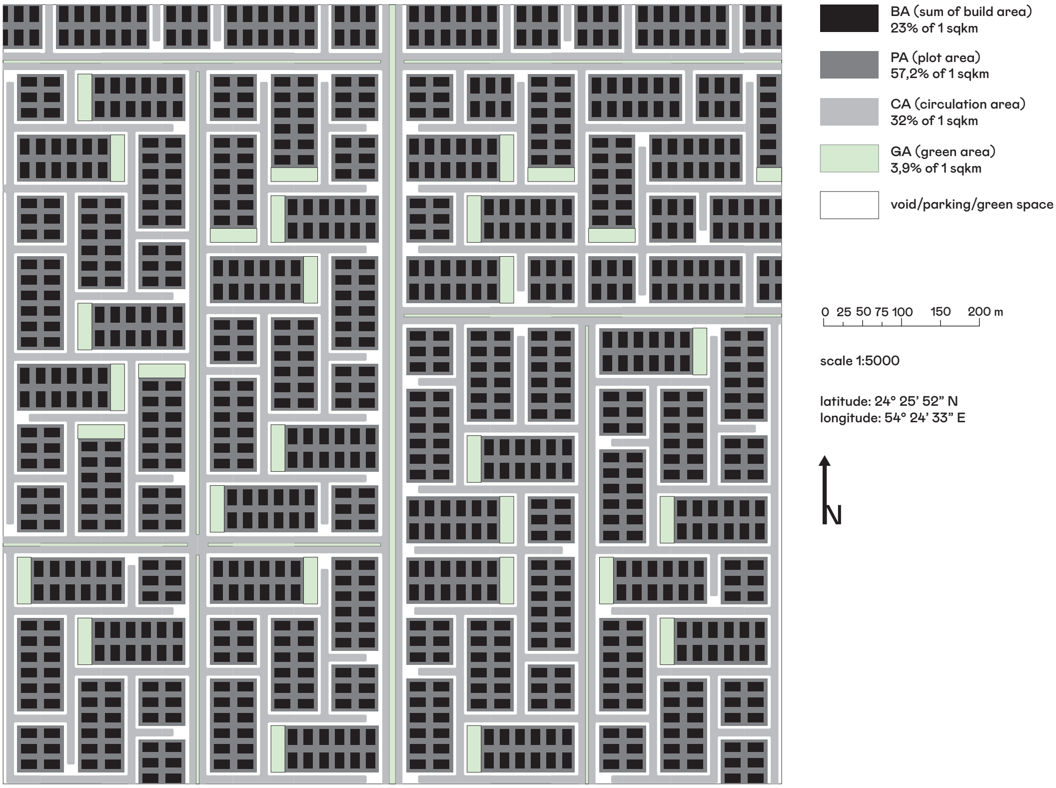


FIGURE 41
Idealised urbanisation pattern based on the Muscat Building Code regulations.

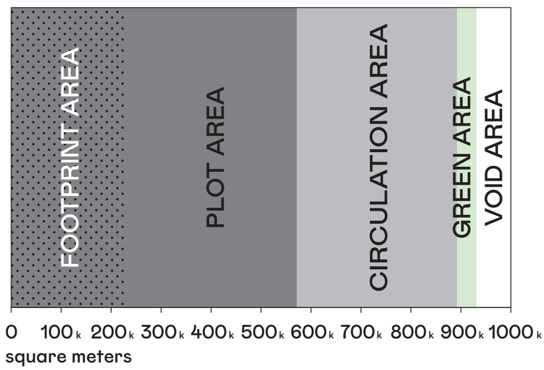


FIGURE 42
Quantitative comparison of analysed areas for the idealised implementation under the Muscat Building Code regulations.

The Al Khoudh sample in Muscat Municipality was planned as a residential urban expansion from ca. 2006 onwards (SEE FIGURE 35). The snapshot taken in 2013 shows barely 7% of the designated plots built. This neighbourhood is a typical example of the land allocation lottery that distributes the uniform 20×30 m plots to Omanis. In its ideal, complete state this sample would have a total built-up area of 24.4% and a total green area of 10.6% (SEE FIGURE 36). Due to lack of incentives, taxation and a burgeoning secondary real estate market the overall development remains far below these figure. The land allocation lottery has been criticised by Al Gharibi and Al Shueili and examined by the author and co-authors (see excursus: Agent-based model of residential behaviour.) 306

The Al Mouj 'The Wave' sample is the prime example of an integrated tourism complex (ITC) developed by the Majid Al Futtain Group – owners and developers of shopping malls and hotels all over Asia and Africa – from 2006 onwards (SEE FIGURE 37). This particular form of real-estate is the only one accessible to foreigner investors from the outside and a testing ground for the liberalisation of foreign investment. The integration of urban design principles within the relatively larger area can be considered a type of 'form-based code'. 307 As such it features mixed uses and an integrated road- and facilities network, shared semi-public spaces and controlled parks. The residential neighbourhoods features several types of buildings and dwelling types ranging from small apartments to row-houses, villas and small residential towers. The quality of the houses is relatively high and energy-efficient. The use of space is considered and the development responds to a market demand. Sonja Nebel questioned the social exclusivity and (in-)accessibility of many parts of the Omani society as such ITCs lay the ground for gated communities and social segregation while occupying prime real estate. 308
The authors conclude from the study of ITCs that urbanisation principles in Oman (and elsewhere) need to be socially sustainable: *"Social sustainability means a socially inclusive city that integrates all parts of society into the current urbanisation process, as social segregation creates inequality and urban uniformity. Mixed urban developments accessible to all parts of society would*

306 Al Gharibi, "Urban Growth from Patchwork to Sustainability Case Study: Muscat"; Al Shueili, "Towards a Sustainable Urban Future in Oman: Problem and Process Analysis."
307 Parolek, *Form-Based Codes*.
308 Nebel, "Tourism and Urbanization in Oman: Sustainable and Socially Inclusive?"

create resilient cities of the future. A more inclusive development could be achieved when also reconsidering current types of Integrated Tourism Complexes (ITCs), as they cater to a small and affluent part of society only yet graft onto expensive infrastructure projects paid for by the government (roads, ports, airports).” [309] The total sealed area is 38.5% while the total green area is 8.6% for this sample (SEE FIGURE 38).

The Fanja oasis village near the town of Bid Bid, in the Ad Dakhiliyah region, in north-eastern Oman, is an example of the rural-urban transformation that initiated in ca. 1995 on the outskirts of Muscat (SEE PHOTOGRAPHS IN PART 3 AND FIGURE 39). This former rural oasis is situated right next to the highway linking Muscat Capital Area with the hinterland. Car-based mobility has turned this oasis village into a suburb of Muscat, but while in decline, the agricultural activity continues. This accounts for a large amount of green spaces, adjacency of green and built spaces and shared spaces. Yet all these spaces are under threat. The expansion process witnessed here is not initiated by the oasis settlement but encroaches upon the rural areas from the outside. [310]

The total sealed area is 11.5% while the total green area is almost double with 21.7% for this sample (SEE FIGURE 40).

The current urbanisation model in Oman can be characterised as urban sprawl. The author has already established an indicator framework for urban sprawl in Oman based on Burchell (SEE TABLE 7): [311]

309 Nebel and von Richthofen, “Urban Sustainability in the Omani Context,” 252.
310 von Richthofen, “Vanishing Omani Landscapes”; von Richthofen, “No Urban Desert! Emergence and Transformation of Extended Urban Landscapes in Oman.”
311 Burchell et al., *The Costs of Sprawl – Revisited.*

	(BURCHELL ET AL. 1998)	ADAPTION TO OMAN
1	Low residential density	Free-standing single-family houses
2	Unlimited outward extension of new development	Expansion into the Batinah Coastal plain
3	Spatial segregation of different types of land uses through zoning	Spatial segregation and zoning cemented by Weidleplan Structure Plan of 1991
4	Leapfrog development	Leapfrog development of major governmental projects leading to insular pockets of development.
5	No centralized ownership of land or planning of land development	No centralized ownership of land due to redistribution per lottery, lack of land development and monitoring tools
6	All transportation dominated by privately owned motor vehicles	All transportation dominated by privately owned motor vehicles, not public transport
7	Fragmentation of governance authority of land uses among many local governments	Hierarchical structure of governance authority of land uses among governmental institutions
8	Great variances in the fiscal capacity of local governments	Centralized financial and political power in Muscat
9	Widespread commercial strip development along major roadways	Widespread commercial strip development along major roadways, including shopping malls
10	Major reliance on a filtering process to provide housing for low-income households	State-sponsored land allocation system per lottery fosters fast consumption of land.

TABLE 7
Urban sprawl characteristics – Indicators for Muscat based on Burchell. 312

We can now ask how these criteria for urban sprawl in Oman relate to the sample and how they can be addressed. The co-authors argue that: *"In order to foster sustainable urbanisation patterns, settlement structures have to be designed on a neighbourhood/city quarter level. The basic unit – the individual plot – is not at all suitable for creating an environment that shows qualities such as: resource-efficient land use, privacy, community space, green areas, shaded public space, energy-efficient buildings, streets for cars and pedestrians. Adapted physical planning standards and building regulations will provide the legal background. Urban design at the neighbourhood level might also revive the traditional* 'hara' *that was based on clustering houses around public and semi-public space."* 313 The predominant residential unit remains the villa as nucleus home for Omani families. This building type is currently the only one promoted by the developers, and legally acceptable under the building code and evident in all the samples, especially in Al Khoud. Taken literally, the current building code can only achieve a 23% built-up area efficiency, while requiring almost the same space for roads and leaving a mere 3,9% for green spaces (SEE FIGURES 41 AND 42). The current urbanisation model prevalent in Oman has reached a dead end.

312 Burchell et al.
313 Nebel and von Richthofen, "Urban Sustainability in the Omani Context," 256.

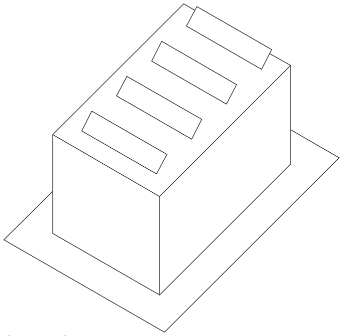
The Al Khoud example also shows that lack of integrated planning and careless distribution of land leads to urban sprawl. The scale of this sprawl hinders the implementation of any kind of resource management and is, above all, a huge waste of space. Any new development needs to take the socio-cultural requirements for privacy into account. Yet, diverse residential units and building typologies emerge in the ITCs of Al Mouj and can also be found in the vernacular architecture of the old oasis core in Fanja. Densities can increase as shown by the alteration and maturity process of Al Khuwair, as in the planned development of Al Mouj. Integrated planning of services, roads and shared spaces adds to the value of the development, yet needs to be socially accessible and fair. Finally, green spaces, requiring massive irrigation, need to serve multiple purposes and should be integrated into the planning of a neighbourhood. These integrated green spaces would exemplify the ecosystem services in Oman and at the same time be agricultural land, regulators of micro-climate through shading and evaporation, bio-filters for water, recreational spaces and stepping stones for biodiversity.

LOW-RISE HIGH-DENSITY ALTERNATIVES

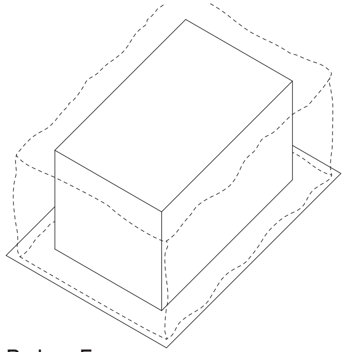
This thesis develops a low-rise high-density (LRHD) neighbourhood for Oman as a response to urban sprawl with the: *"desired targets and indicators for the urban design model: To create a walkable city, reduce commuting [by private vehicles], allow efficient land use, enable low energy consumption, and create social and economic diversity in response to the prevailing sprawl in Muscat Capital Area."* [314]

- Low-rise high-density alternative take inspiration from the form-based code present in the 2010 Emirati residential neighbourhood scheme: *"The model is also built-upon the UAE-wide housing concept 'Estidama', developed by the Abu Dhabi Urban Planning Council (UPC) to address rapid growth as part of the 'Plan Abu Dhabi 2030' urban master plan.* [315] *Estidama, literally translates as 'sustainability', and incorporates many aspects of passive energy efficiency and smart neighbourhoods into an Arab context."* [316] The architectural features of the 'Estidama' housing concept are illustrated here (SEE FIGURE 43):

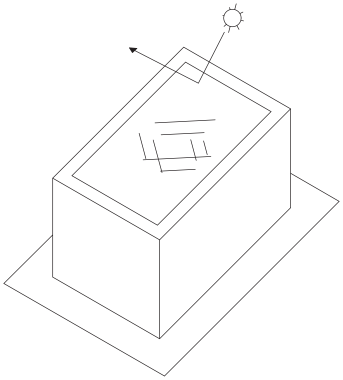
314 von Richthofen, "Modelling Low-Rise High-Density Neighbourhoods in Oman," 197.
315 Abu Dhabi Urban Planning Council, "Estidama."
316 von Richthofen, "Modelling Low-Rise High-Density Neighbourhoods in Oman," 192.



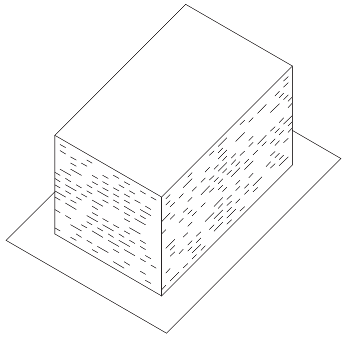
Solar Collector
Use sunlight for hot water and electricity.



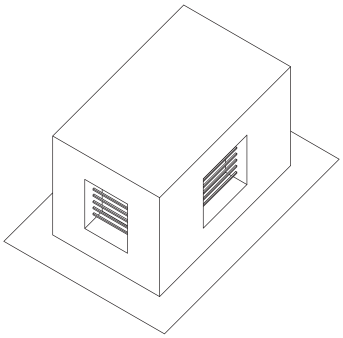
Reduce Energy
By using efficient systems and insulating materials.



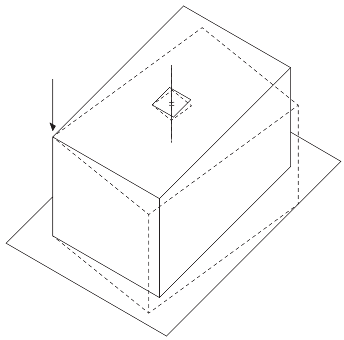
Cool Roof
External surfaces that reflect solar gain back to atmosphere.



Low Impact Materials
Specify materials that are non-toxic, local and recycled.



Minimise solar gain
By increasing depth of recess to windows or add louvers/mushrabiya.



Orientation
Maximize daylight, minimize solar gain.

FIGURE 43
Sustainable architectural features of the 'Estidama' housing concept.

Such a low-rise high-density (LRHD) neighbourhood could be based on criteria developed by Burchell (SEE TABLE 8): 317

	(BURCHELL ET AL. 1998)	ADAPTION TO OMAN
1	High residential and employment densities	High and decentralized residential and employment densities
2	Mixture of land uses	Mixture of land uses
3	Fine grain of land uses (proximity of varied uses and small relative size of land parcels)	Fine grain of land uses (proximity of varied uses and small relative size of land parcels) on neighborhood level
4	Increased social and economic interactions	Increased social and economic interactions
5	Contiguous development (some parcels or structures may be vacant or abandoned or surface parking)	Contiguous development including agriculture and recreational uses
6	Contained urban development, demarcated by legible limits	Legible urban development, preservation of past urbanization, architecture and landscape development
7	Urban infrastructure, especially sewerage and water mains	Accessibility urban infrastructure, especially sewerage and water mains
8	Multimodal transportation	Multimodal transportation, encouraged shared mobility
9	High degrees of accessibility: local/regional	High degrees of accessibility and connectivity: local/regional
10	High degrees of street connectivity (internal/external), including sidewalks and bicycle lanes	High degrees of street connectivity (internal/external), including shaded sidewalks and bicycle lanes
11	High degree of impervious surface coverage	High degree of impervious surface coverage
12	Low open-space ratio	Low open-space ratio combined with high floor-are-ratio
13	Unitary control of planning of land development, or closely coordinated control	Unitary control of planning of land development and management including local participation
14	Sufficient government fiscal capacity to finance urban facilities and infrastructure	Sufficient government fiscal capacity to finance urban facilities and infrastructure after the oil-based economy

TABLE 8
Compact city characteristics – LRHD urban fabric for Oman based on Burchell. 318

The parameters for such a LRHD residential neighbourhood developed for Oman include: Building footprints, outdoor space, sealed surfaces, shaded areas, green space, street and curbside space. 319

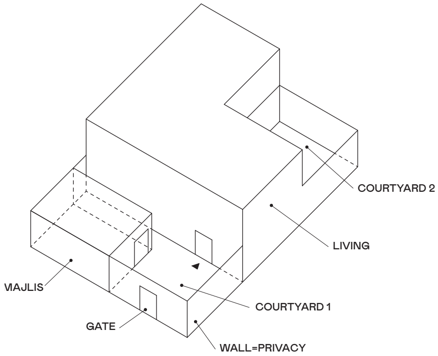
317 Burchell et al., *The Costs of Sprawl – Revisited.*
318 Burchell et al.
319 von Richthofen, "Parameters of Urban Expansion in Oman," 110.

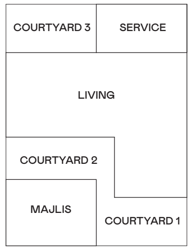
PROTOTYPE DESIGN

These design principles translate into a generic architectural scheme that developed by the author in 2016:

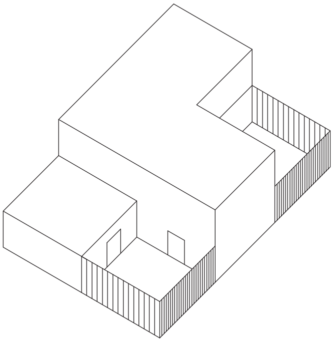
> *"A courtyard type house has been chosen as Basic Building Unit. This house occupies a 15×20 m plot (300 m²) representing exactly half of the plot size currently allocated to by the governmental lottery system to all adult Omanis. This reduced plot size offers nonetheless offers the same floor area of approximately 310 m² by using a denser building typology. It also offers a locally adapted typology with a 'majlis' (guest room) in the front and the desired privacy in form of a courtyard to the back. Public and family functions can be easily separated. The 15×20 m plot can be segmented into six parts of ca. 7×7 m. Four of these six segments can be built-up with an average of two floors. By shuffling the four elements over the six possible parts a catalogue of expansion possibilities can be produced. This Basic Building Unit utilises passive means of energy preservation: solar collectors for hot water and electricity production, efficient insulation materials, reflective roofs to reduce the solar heat impact, use of low-impact local materials, natural lighting from the roof, water-efficient landscaping for outdoor shading, optimal orientation of house and openings facing west.*
>
> *The Basic Building Units can be assembled in small clusters. These groups of houses will provide shade and create narrow, naturally shaded and ventilated Sikkas (pathways). The size of the clusters is determined by a maximum distance of 80 m considered walkable under the climatic conditions in Oman. Cul-de-sacs roads penetrate the neighbourhood, but prevent through traffic. This ensures priority of pedestrian mobility. Several clusters form a Barahaat (neighbourhood), where streetscape and building footprints form an intricate and intertwined urban fabric. Public spaces, small shops, schools and mosques are located around multiple centres throughout the neighbourhood. Arterial green strips fed with recycled grey water complete the LRHD Neighbourhood."* 320

320 von Richthofen, "Modelling Low-Rise High-Density Neighbourhoods in Oman," 198.

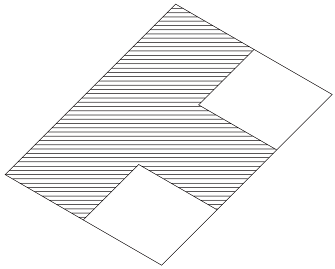




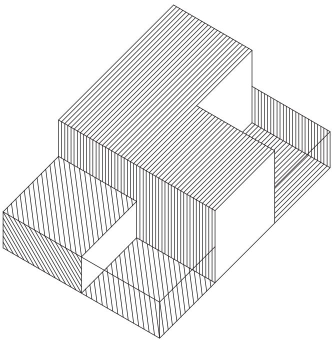
Courtyard House



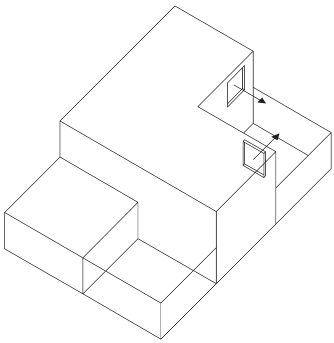
1. Privacy



2. Optimum use of land



3. Separation of the private family space from the semi-private guest space



4. Internal rooms overlook the family courtyard

FIGURE 44

Generic sustainable architecture concepts adapted to the Omani climate for a 15×20 m 300 m² plot.

The generic architectural concept forms a versatile building block of the new residential and agricultural neighbourhoods. The Basic Building Units can be built as free-standing single units next to fields. They can fill in the existing plot lines of currently 20×30 m as they are exactly half the size, so that two units occupy can one plot. The Basic Building Units can further be linked to form row-houses in any length or configuration. Each house will then shade parts of the neighbouring house, while courtyards can be shielded from outside view for privacy. The modular grid of 7×7 m enables not just an incremental phasing suitable to the needs of a family, but also expansion upwards, as units can be placed on top of roof terraces. Courtyards and interstitial spaces can be linked to agricultural use so that their ecosystem service benefits of shading, evaporative cooling and recreational use go hand in hand with food production and waste water treatment (SEE FIGURE 44).

In a first prototype developed and parametrised using the software Grasshopper (SEE FIGURES 45–47). [321] The Basic Building Units forming neighbourhoods as residential clusters are served by cul-de-sacs streets. Shared spaces of back-lanes or ‘sikka’ offer shaded pedestrian mobility spaces. Commercial and communal facilities are located at the end points of the cul-de-sacs. The scheme is benchmarked quantitatively against the Al Khoud neighbourhood. It scores significantly higher due to the increased density and better land use since it only requires plot sizes of half the ones in Al Khoud. But this obvious advantage applies to other ratios such as street length to inhabitant that improve as well.

321 “Grasshopper.”

FIGURE 45
Parametric model of a residential prototype neighbourhood for Oman based on a Low-Rise High-Density scheme of 15×20 m 300 m² plots.

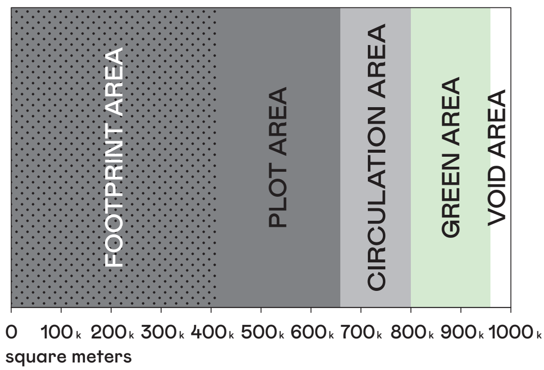


FIGURE 46
Quantitative comparison of analysed areas for the parametric prototype (proportionally scaled to 1×1 km area).

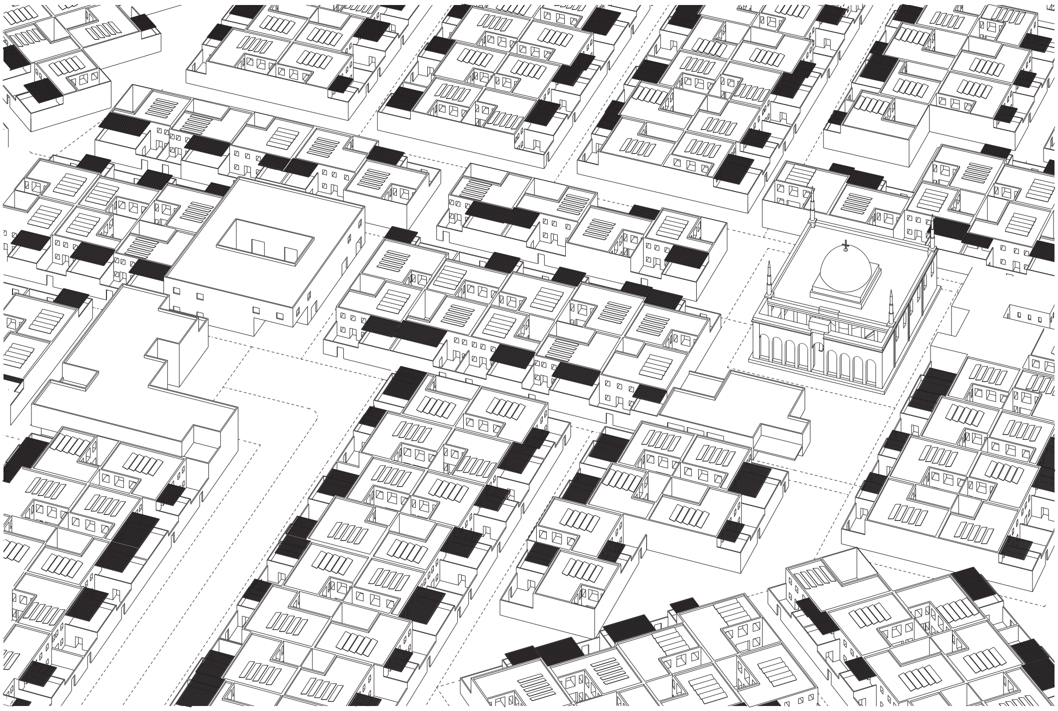


FIGURE 47
Visualisation of the residential prototype neighbourhood for Oman, 2014.

The residential prototype has several drawbacks that need to be addressed and improved for the residential-agricultural scheme: It is not yet fully scalable yet due to the cul-de-sacs road network system. It does not yet integrate agricultural land use. Despite the parametric generation of the urban form, modification of the underlying road network and plot division is difficult in Grasshopper. The quantitative evaluation is also not integrated. Finally, it does not react to underlying geographic information.

To improve these shortcomings a second parametric model has been developed with the software CityEngine. 322 This software package allows creating urban geometries (roads, surfaces, plots, vegetation and buildings) in three dimensions based on parametric rules. land cover maps can act as underlying parameters for the expression of rules. The CityEngine model reads three land cover classes – barren land (white), agricultural land (green) and urbanised land (red) – to drive the urban model. The colour value of the maps at a specific geo-referenced location is linked to parametric

322 "Esri CityEngine."

rules and becomes an input parameter setting the 'land cover' attribute. In this way one can achieve a gradient from unbuilt barren land, sparse agricultural land, mixed agricultural and built-up land, to fully built-up land. CityEngine is not a land cover change predictor. An automated simulation of land cover change has not been undertaken in this thesis. Instead, the projected land cover is the result of a contextual analogue urban analysis for the selected cases.

At the base of the CityEngine model is a version of the Omani 30×20 m plot cut in half with subdivision into six parts of ca. 7×7 m. It contains a 'growth' algorithm for streets that replicate the Omani street layout while reacting to topographic conditions. The prevailing grid orientation can be designed according to contextual and environmental requirements. land use can change in a gradient from fully agricultural to fully built-up and back. This is driven by GIS maps generated by remote-sensing. Parameters are controlled by so called rule files – codes – that generate shapes in three-dimensional geometry. A dashboard reads and displays the key quantitative data. Design variations can be stored as scenarios and compared visually and quantitatively. The results are available as interactive three-dimensional web-scenes to be viewed in a browser.

ALGORITHM STRUCTURE

CityEngine applies the concept of shape grammars developed by Gips in a generative three-dimensional geo-information system (SEE FIGURE 48). 323

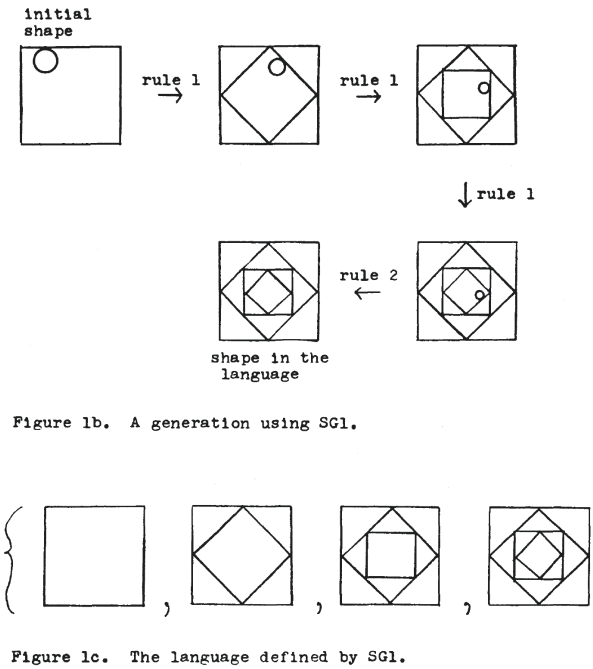


FIGURE 48
"Shape Grammars and the Generative Specification of Painting and Sculpture" by George Stiny and James Gips, 1971.

The basic principle of CityEngine is to compute with shapes. The typical computation sequence is to take input shapes, apply transformation rules and generates new shapes (SEE FIGURE 49). These shapes can be the starting point of a new transformation and result in new shapes. CityEngine uses its own scripting language CGA (Computer Generated Architecture) that is similar to other scripting languages like Java or Python. *"CGA (Computer Generated Architecture) shape grammar is a unique programming language specified to generate architectural 3D content."* 324

323 Gips, *Shape Grammars and Their Uses*, 10.
324 "Esri CityEngine."

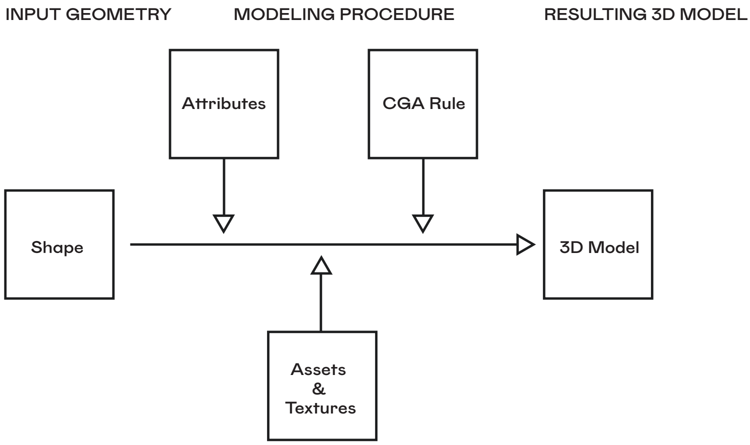


FIGURE 49
Diagram of shape computation in CityEngine.

The user interface offers several windows for visual and numeric output: 1) Scene Editor (for scene, layer, and object management); 2) Rule Editor (to edit the code); 3) Navigator (to manage and preview files in the workspace); 4, 5) Viewport (to visualise the geometry in three-dimensions); 6) Inspector (Shape Parameters, Rules, Reports, Object Attributes, Vertices); 7, 8) Console (viewing CGA or Python output) (SEE FIGURE 50).

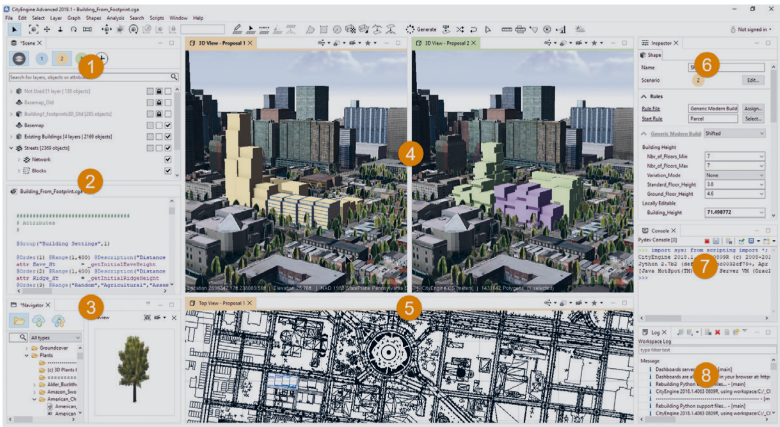


FIGURE 50
CityEngine user interface (ESRI, 2018).

CityEngine offers basic generative functionality for the generation of shapes (Euclidian geometric representing objects, buildings, etc.) and graphs (networks representing roads or circulation infrastructure). The logic of CityEngine requires graphs that will generate plots automatically based on several computationally intense algorithms. In CityEngine the street will always create the plots on which the buildings 'grow'. This has the advantage that modification of the street network immediately reflects in the subdivision of plots and the resulting urban form. The graph network algorithm is constrained by parameters of minimum and maximum segment length, ranges of curvature angles and degree of randomness. The overall segment number is also specified. While the graph network algorithm cannot be directly modified by coding almost all options can be achieved in combination of these parameters. CityEngine features an extensive library of transformation commands that allow to create almost any Euclidian geometry. There are also numerous editing possibilities to manipulate the geometry next to importing and reparametrising geometry, too. It is also possible to grow shapes of plots that are not bound by a graph network. The same shape-rule-shape workflow applies but the link between graph network and plots is then obviously lost. It is therefore good practice to start with a graph network and to conceptualise the city to be developed from it as a sets of parametric transformation rules. This will allow maximum scalability and transferability.

In practice, designers need to develop a design strategy that combines pre-processed input geometry with specific rules that follow the coding logic. There is a trade-off between parametric flexibility of rules and scenes and complexity of code. A good code will break down design parts into sub-codes for specific shape computation. The strategy chosen and the code blocks are explained here.

Initial Attributes: Declaring attributes allows setting parameters for desired transformation rules. An extrusion, for instance, will require a shape to extrude and an extrusion height. This value in metres can be declared as attribute. Attributes also show up in the editor and can be controlled and set individually overriding the pre-set values. Depending on the rule design and complexity more attributes might be necessary.

The street grid: A special code developed in Python was necessary to create the nested rectangular grid of streets typical for Oman. This Python script invokes the graph network and creates road segments. These can be joined in a second stage to form the continuous street grid. This grid represents the typical situation of the status quo. Modifications can be done by changing the parameters of the Python script or by using the parametric growth algorithms built into CityEngine (SEE FIGURE 51).

```
from scripting import *

# get a CityEngine instance
ce = CE()

if __name__ == '__main__':
    nX = 4
    nZ = 4
    ox = 0
    oz = 0
    l  = 160 #200
    s  = 80 # 100
    graphlayer = ce.addGraphLayer('streets')
    for ix in range(0,nX):
        for iz in range(0,nZ):
            x = ox+ix*s
            z = oz+iz*s
            # Short vertical 1
            vertices = [x,0,z, x,0,z+s]
            shape = ce.createGraphSegments(graphlayer,  vertices)
            # Short Horizontal 1
            vertices = [x,0,z+s, x+s,0,z+s]
            shape = ce.createGraphSegments(graphlayer,  vertices)
             # Short vertical 2
            vertices = [x+s,0,z+s, x+s,0,z]
            shape = ce.createGraphSegments(graphlayer,  vertices)
             # Short Horizontal 2
            vertices = [ x+s,0,z, x,0,z]
            shape = ce.createGraphSegments(graphlayer,  vertices)
```

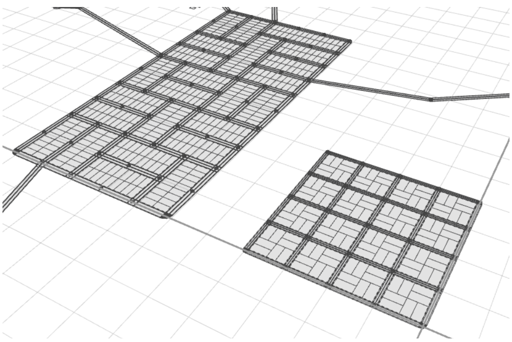


FIGURE 51
Rectangular graph network algorithm for Oman implemented in CityEngine.

The plot subdivision: The plot subdivision is controlled by setting the parameters in the CityEngine Inspector window. These are set to tight minimum and maximum edge lengths as well as area sizes. CityEngine assigns a frontside to all generated plots and orients all plots towards the main road side. This creates undesirable rotations of the plots in the corners that needs to be addressed in the script (SEE FIGURE 52).

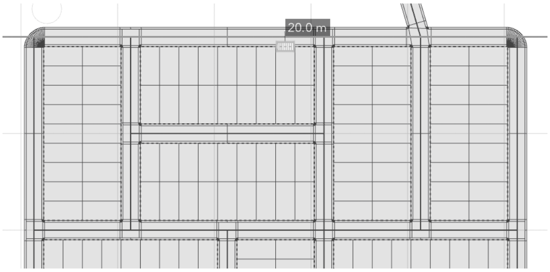


FIGURE 52
Detail of parametric plot subdivision implemented in CityEngine.

The buildings: The buildings are based on a grid division of 2×3 cells resulting in six cells. These six cells can be filled or not filled to create cubic elements of the house. The pattern is encoded as a string where a 'blank' represents no fill and a '0' a fill. The string sets that pattern in X and Z direction. A different cell arrangement needs to be encoded into the string pattern, e.g. a grid of 3×4 cells would require three rows of four strings in quotation marks, and so on.

```
@Percent
attr coverage = 1

const patternX = 3
const patternZ = 2

// Pattern according to coverage
// An "0" encodes a filled tile
pattern =
case coverage > 0.80:
" O "+
"OOO"
case coverage > 0.60:
" O "+
" OO"
case coverage > 0.40:
" O "+
" O "
case coverage > 0.20:
"   "+
" O "
else:
"   "+
"   "
```

The string is read and stored in substrings:

```
// extract single letter from string
charAt(string, index) = substring(string, index, index+1)
```

The building footprint is created by splitting the plot into the desired quantity in X direction followed by a split in the desired quantity in Z direction. The pattern is then read from the string and filled if the condition “0” is true, or else it remains empty.

```
// split plot into patternX parts along x axis
Combination-->
split(x) {'(1/patternX):Z_Split(split.index)}*

// split the three parts into patternZ tiles
Z_Split(x_idx)-->split(z) {'(1/patternZ):Tile(x_idx, split.index)}*

// use split index along x axis and split index along z axis to compute pattern
string position
Tile(x_idx, z_idx)-->

// extract letter from pattern string. If it is an "0", fill the tile
case charAt(pattern, z_idx*patternX+x_idx) == "0":
Filled
// otherwise empty tile
else:
Empty
```

The filled sub-parcels are then extruded to produce the cubic volumes of the buildings.

```
Filled-->

    report("Plot.Footprint_Area", geometry.area)

    extrude(FloorHeight*FloorNumbers) X
```

This process can be continued to model all desired elements of the building to facade details and beyond. We opted for an abstract representation with the reporting of key figures (SEE FIGURE 53).

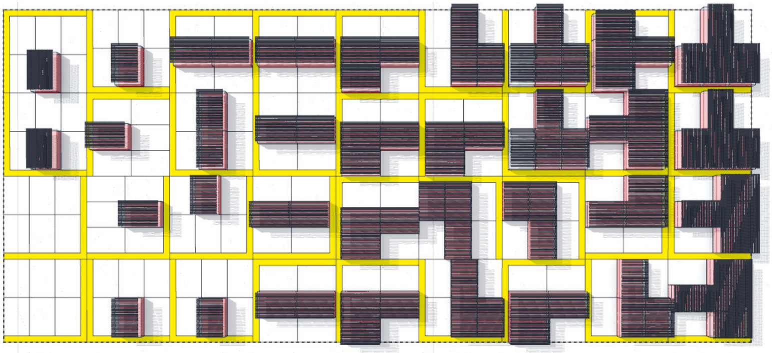


FIGURE 53
Building prototype implemented in CityEngine.

Reports: Several reports can be generated from the script by simply adding the line of code ‘report’. These reported figures can be combined to meaningful values, sums and ratios and visualised in a dashboard (SEE FIGURE 54).

```
Filled-->
report("Plot.Footprint_Area", geometry.area)

Yard -->
color(0,1,0)
report("Plot.Green_Area", geometry.area)

Floor --> comp(f) {bottom: W }

W --> //color(1,0,0)
report("Gross Floor Area (GFA)", geometry.area)

L --> color(1,1,0)
report("Plot.Circulation_Area", geometry.area)
```

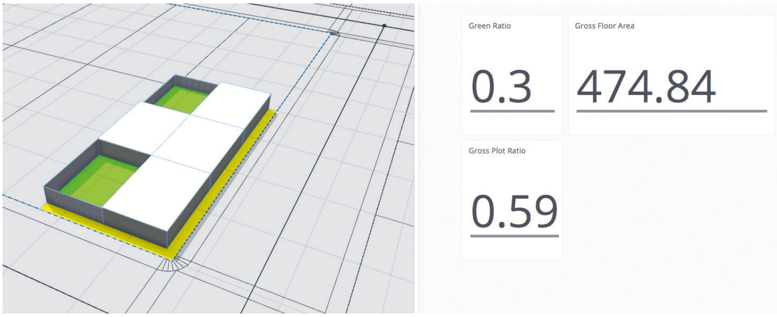


FIGURE 54
Simple data dashboard implemented with CityEngine.

Agricultural-Residential Gradient: The agricultural-residential gradient is achieved by linking the plots to two underlying raster images: the remote-sensed status quo of 2017 and the projected spatially diverse alternative. The CityEngine rules visualise both scenarios. It is important to note that the remote-sensed maps are always oriented north-south and have a spatial resolution of 15×15 m. The streetgrid and resulting plots in CityEngine will probably not be oriented this way and will have a different grid spacing. In other words, a small shift in the location of the geometry might result in a different reading of the input map pixel. Therefore, we don't have a direct congruent match between the remote-sensed map and the rule based geometry, which was never intended anyway, but needs to be declared in order to avoid misunderstanding about the approach. The inherent mismatch is embraced as 'fuzziness' and does not reduce the validity of the results on a larger scale of a neighbourhood (SEE FIGURE 55).

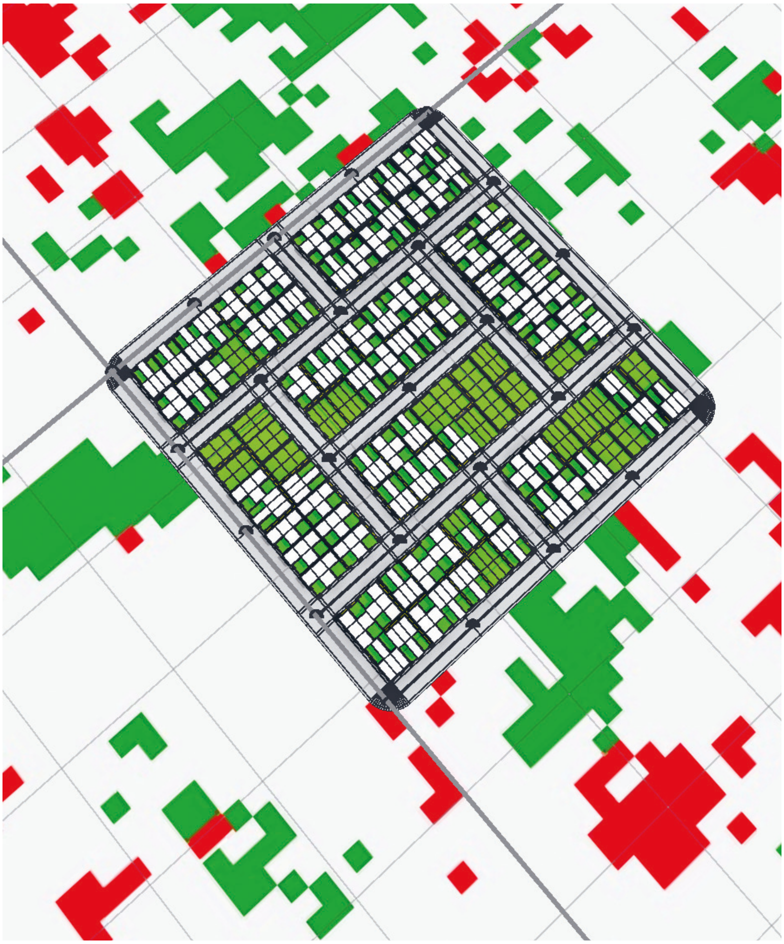


FIGURE 55
Agricultural-residential gradient implemented in CityEngine showing the land cover classes barren land (white), agricultural land (green) and urbanised land (red). ●

PART

IV

FINDINGS

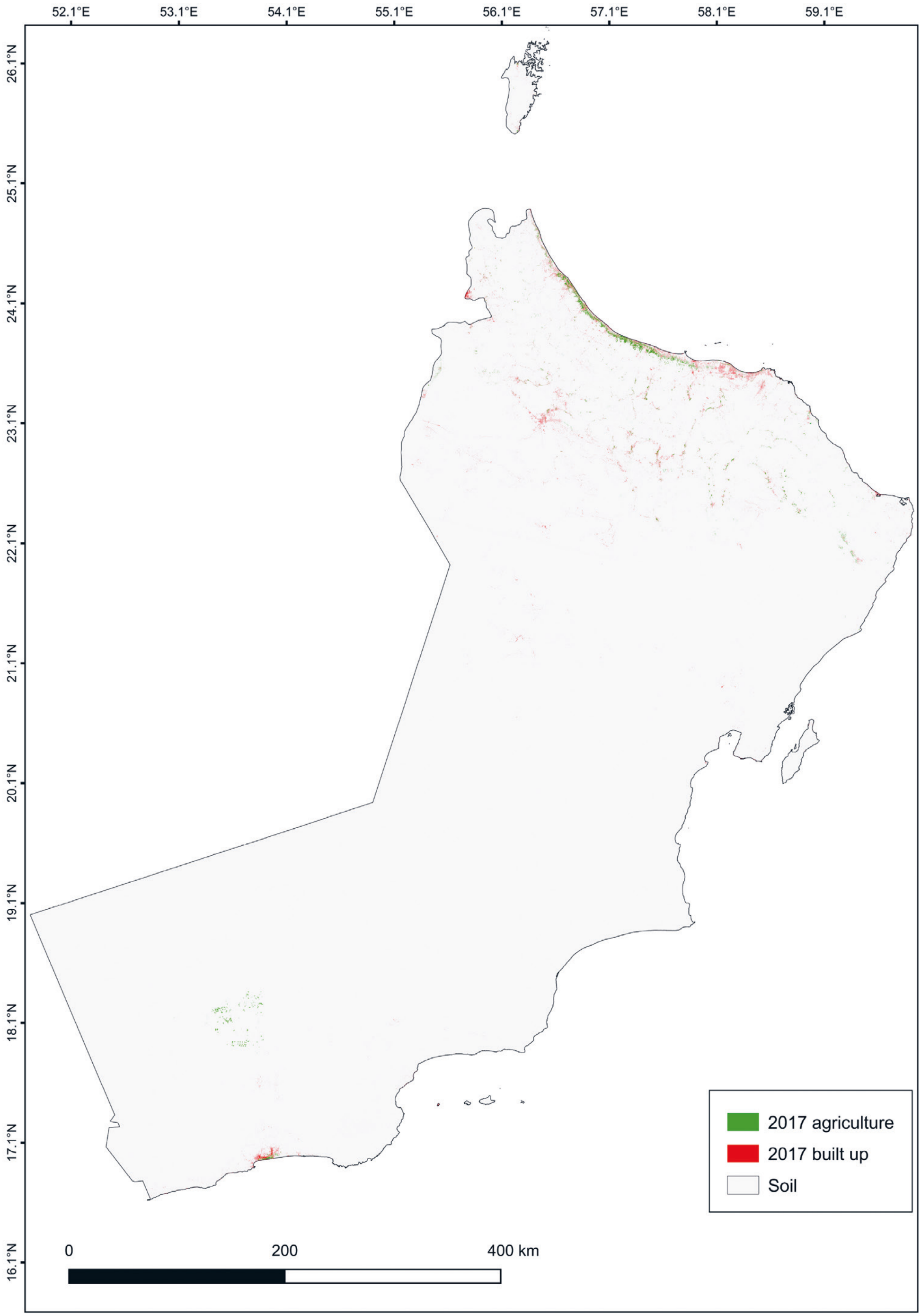


FIGURE 56

National Map of Oman 1000×1500 km, 1:5.000.000, 2017.

PART 4: FINDINGS

The application of remote-sensing to historic satellite images in Oman reveals the land transformation morphology of the whole country for the first time. The remote-sensing survey has been conducted in nested scales from the national to the regional to the local scale. It allows identifying locations, rates of change and scales of land use transformation.

Locations of land use transformation: The national scale observation reveals that urbanising regions are located along the northern shores of Oman, originating from Muscat and reaching towards the border with the United Arab Emirates in the north. This urbanisation stretches along the Al Batinah coast and runs parallel to the Hajar mountain range and the Omani interior. A further urbanisation nucleus is located in the southern coast with a sub-centre in Salalah.
Rates of change of land use transformation: The rates of change are visible from a historic comparison of land use transformation with the present situation. This reveals a fast moving rural-urban interface that changes former rural areas into suburban areas. Historic urban centres in Muscat Capital Area and Salalah are relatively stable, while the former gravel desert and oasis territory is under threat or rapid urbanisation.
Scales of land use transformation: The scales of land use transformation imply both spatial and temporal dimensions. The findings indicate an advancing rural-urban interface that transforms agriculture spaces in unprecedented speed and scale. The implication and scale of transformation is national and mobilises all resources, even those from remote areas, in this transformation process.

Based on these criteria the dissertation further investigates the larger region of Muscat Capital Area (100×50 km), the Al Batinah region (50×50 km), the Omani interior region surrounding Nizwa (50×50 km) and the southern region of Salalah (50×50 km). Muscat Capital Area was analysed with six local samples; the others with three local samples each; totalling 18 local samples of 2×2 km (each indexed with a letter a-e below). The national scale serves to identify the main patterns of land use transformation. It juxtaposes the two main land uses surveyed – agricultural and urban land – for the most recent time stamp of 2017. The five regional-scale case studies are discussed, based on three maps each: the temporal development of agricultural land use from 1990–2017, the temporal development of urban land use from 1990–2017 and the juxtaposition of agricultural and urban land uses for 2017. The 18 local samples are also presented as a set of three maps each showing the temporal development of agricultural land, urban land and the most recent juxtaposition of agricultural to urban land for 2017. This last timepoint of 2017 is further analysed statistically to determine the spatial diversity. The features of these maps are counted and their area as well as perimeter recorded to determine their 'space species' distribution. The diversity of these 'space species' is then analysed using Shannon's diversity model.

LAND USE MAPS AND SPATIAL DIVERSITY INDICES NATIONAL SCALE

The national scale observation reveals land transformation patterns that are significantly different from previous descriptions. Land transformation patterns in Oman were linked to generic concepts such as 'urban sprawl', [325] 'urbanisation of the coastline' [326] and the unidirectional 'rural-urban transformation'. [327] These generic concepts do apply to Oman but don't suffice to explain the particular form of land use transformation that is occuring. Expanding urbanisation of the desert territory, as articulated by ETH Studio Basel in 2013, had not been critically included. [328] As is visible in the national scale map, the land use transformation expands along road networks and encroaches upon those areas that can be served with fresh water at moderate costs. This explains why former oasis villages and the agricultural areas are under particular risk. The process of land use transformation is increasing in speed as the size as settlement cores increase. The pressure of land use transformation is omnipresent in urban, urbanising and rural regions alike in Oman. The particular findings for each observed region are (SEE FIGURE 56):

325 Al Shueili, "Towards a Sustainable Urban Future in Oman: Problem and Process Analysis."
326 Belgacem, "Is Littoralization Reconfiguring the Omani Territory?"
327 Dutton, *Changing Rural Systems in Oman*; Abdelaal, "Rural Urban Linkages for a Sustainable Oman: The Case Study of Transformation in Fanja."
328 Jovanovic, Meili, and Diener, "Muscat and Oman – Restructuring a Desert Landscape"; Jovanovic, Meili, and Diener, "Investigating Specificity – Muscat & Oman."

Muscat Capital Area: The former settlement cores such as villages, oasis settlements and infrastructure have blurred into a continuous urbanisation carpet of low-density suburban settlements. The development is constrained geographically by the mountains in the west and the Arabian Sea in the east. The urbanisation gradually blends into the former agricultural land of Al Batinah in the north. The Muscat Capital Area transformation has reached an almost complete level of saturation. At the same time, urban re-densification or re-structuration processes are not visible. In some parts, older development pockets deteriorate and some land is vacant.

Al Batinah: The settlements in the Al Batinah region north of Muscat Capital Area continue to expand as well. The Al Batinah region forms a loosely connected web of settlements intertwined with fragmented oasis and agricultural space. The rates of land use transformation change accelerate here too, while the process of transformation is still ongoing. The scale of transformation of this region is important as the region is Oman's agricultural 'bread-basket'. The process of land use transformation in this region can be described as gradient urbanisation.

Omani Interior: The locations of land use transformation of the Omani interior west of the Hajar mountains mirror the land use transformation and urbanisation processes in Al Batinah along the coast. Instead of a continuous carpet or mat, the interior is characterised by a connected web of settlements. Similar to the development along the coastline, these settlements encroach upon the even scarcer oasis and agricultural spaces. The rates of change and scales of land use transformation in this region of Oman can be described as necklace urbanisation.

Salalah: The southern region of Salalah enjoys a particular seasonal rainfall that supports intensive coastal agriculture. Yet here too the agricultural land is under particular threat by urbanisation. The rates of change and scales of land use transformation in Salalah can be described as radial urbanisation.

These four regional examples underline the argumentation of this thesis that the activation costs of spaces – the costs for land development, infrastructure provision, transport networks and mostly fresh water provision – determine the spatial development potential. In all regional case studies these activation costs can be lowered if a potential urbanisation can be grafted on existing infrastructures, if they are in reach of (other) urban areas, close to available fresh water and with a favourable topography. Desert and mountainous spaces are thus less suitable for urbanisation, whereas the former agricultural land is.

REGIONAL SCALE

The five regional case studies include three in Muscat Capital Area (MCA 1, MCA 2, MCA 3), one in the Omani interior around the town of Nizwa (NIZ) and one in the southern region of Salalah (SAL). These regions are further described in three maps each: the temporal development of agriculture from 1990–2017; the temporal development of urbanisation from 1990–2017; and the juxtaposition of agriculture and urban land use in 2017. These sets of three maps allow adescription of the specific local locations, rates and scales of change.

The first map, MCA 1 – Agriculture, shows how agriculture developed in Muscat between 1990–2017. We can see a significant decline in agriculture in the coastal zones and a shrinkage of oasis areas within the Muscat Capital Area. Some agricultural areas have been given up all together. The process is accelerating and ongoing (SEE LIGHT GREEN AREA FOR THE LOST AGRICULTURAL LAND SINCE 1990 IN FIGURE 57). Artificially irrigated areas appear next to the road network. The second map, MCA 1 – Built-up Area, shows how the built-up area developed in Muscat between 1990–2017. While the urban expansion of Muscat Capital Area started in the 1980s the selected observation frame from 1990 to 2017 allows tracing much of the urban expansion. The map shows the macro-trend of urbanisation along the coast, starting in the historic core of Muscat in the east and going towards the north-west. It further shows how the patchwork of allocated neighbourhoods developed over time, yet remains with low urban density (SEE ORANGE AREA FOR THE BUILT-UP LAND TRANSFORMATION SINCE 1990 IN FIGURE 58). This process takes place at a different scale than the first general vector of urbanisation. The third map, juxtaposes the agricultural and urban land cover and shows that the latter encroaches upon the former (SEE FIGURE 59). This process can be described as urban territorialisation of fragmented agricultural space. Together the maps show that the land use transformation towards an urban environment is almost complete in Muscat Capital Area. The map shows that the remaining agricultural land, rural-urban interface, the urban expansion areas and mature neighbourhoods all merit close attention. The current state of (careless) urbanisation calls for a radical shift in urban spatial production, as the main resource

– space for sustainable urban and agricultural development – is almost exhausted in this region.

The map of MCA 2 – Agriculture shows the shifting modes of agricultural production in a region known to be the 'bread basket' of Oman. The strip of agricultural land in a first line parallel to the coast disappeared. Smaller fragmented agricultural lands vanished within two decades. Both the land close to the shore as well as the fragmented land were historically less productive and harder to maintain and were thus abandoned or converted to urban spaces first. As a result, the remaining agricultural land has been consolidated into compact agricultural areas (SEE FIGURE 60). The MCA 2 – Built-up Area map shows the significant increase in urbanisation and the shifting patterns of land use. Small formerly scattered settlements have now grown into continuous urban sprawl spaces. During the 2000s the region became an urban expansion zone of Muscat Capital Area, shifting the predominant land use from agricultural to urban. The rural-urban interface of this region plays out in fragmented and constrained pockets of agricultural space surrounded by urbanising carpets (SEE FIGURE 61). The final juxtaposition map shows that a formerly continuous agricultural strip running parallel to the coast has been split into two separated and cut-up strips (SEE FIGURE 62).

The MCA 3 – Agriculture map shows the spatial transformation of the area with the predominant agricultural land use located in the north of Al Batinah. As in the other Al Batinah areas we can see agricultural land loss close to the shore as well as in smaller fragmented patches (SEE FIGURE 63). The MCA 3 – Built-Up Area map shows urban development and the gradual connection of all settlement cores into a linear urban development along the highway. The map contrasts increasingly fragmented agricultural land use to gradually more connected and consolidated urban land use. This transport infrastructure-related urban expansion is now also driving inland towards the gravel plains of the Al Batinah (SEE FIGURE 64 AND 65).

The regional maps of Nizwa (NIZ – Agriculture, Built-up Area and juxtaposition, see figures 66, 67 and 68) show a dramatic decline in oasis extent and a rampant urban sprawl as two congruent phenomena. Urban sprawl increases the pressure on both former agricultural land and gravel desert to be converted into buildable land. As agricultural land declines relations shift: the built-up space accounted for 1/10th in 1990, whereas 2/3^{rds} of the land is built up in 2017. Distances between fragmented agricultural land patches increase. Connected and sophisticated ancient irrigation systems decline and are now being superimposed and disrupted by modern settlement patterns.

The map of Salalah shows a decline in peripheral agricultural land use and a fragmentation of the central and coastal oasis and fruit plantations. Smaller and more remote linear oases in particular disappeared between 1990 and 2017 (SEE FIGURE 69). Urban expansion consolidated and densified in central areas. The beachside, former home of coconut plantations, has been fully built up. Fast urban expansion into previously unused land occurred in the north and west. As a result, the remaining agricultural land is highly constrained and fragmented and threatened by further urban expansion (SEE FIGURES 70 AND 71).

All regional scale samples show a decline in agricultural land use and an encroachment of urbanising land use. The urbanisation is firstly directed towards agricultural land and secondly towards accessible gravel plains. Urban expansion contributes to the homogenisation of land use morphologies and significantly reduces the agricultural land use diversity and resilience. The rates of change differ from case to case and accelerate as the size of the urban development increases: Muscat Capital Area and Salalah being the fastest, followed by Nizwa and Al Batinah.

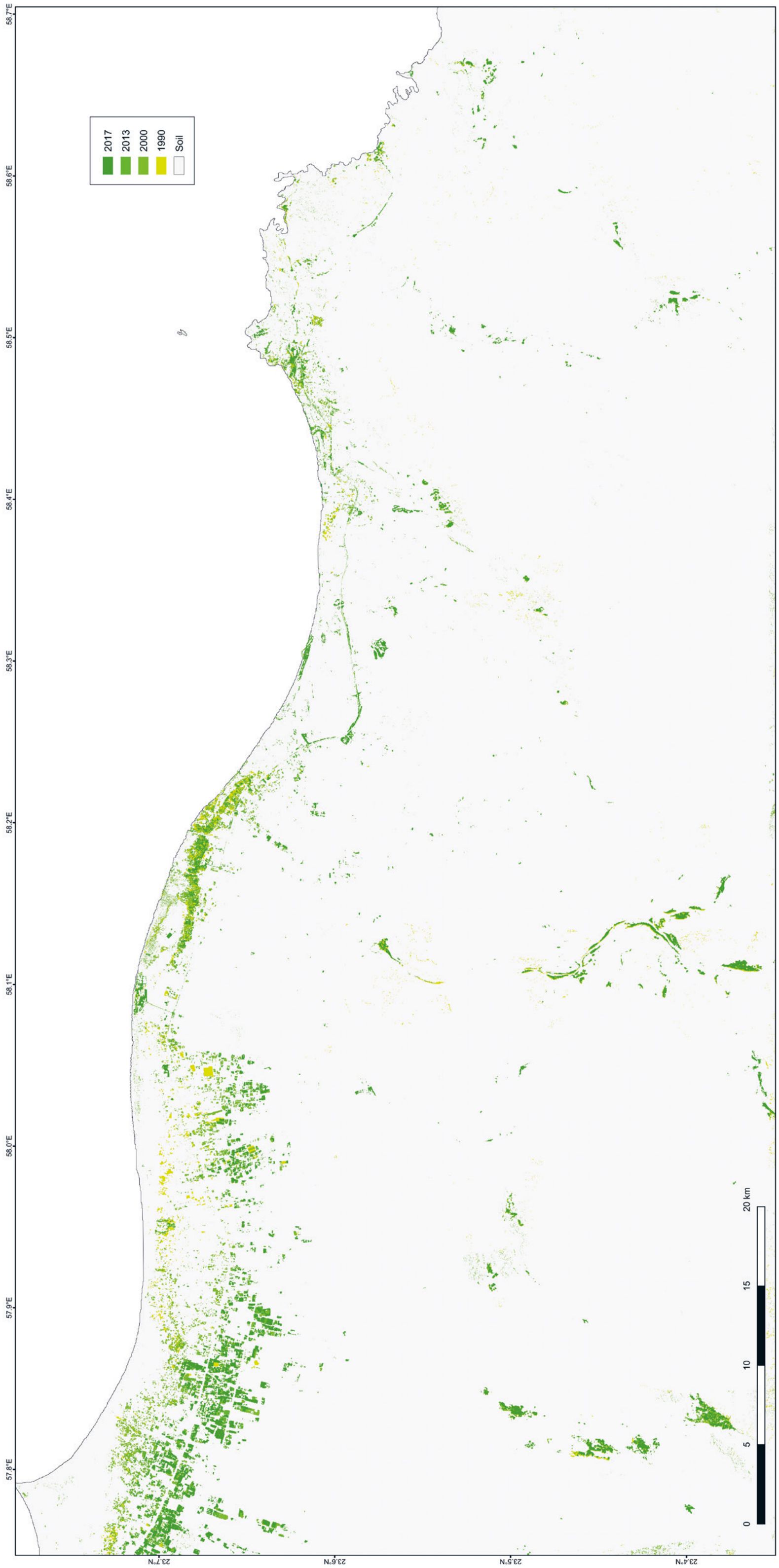


FIGURE 57
Regional Map of MCA 1 – Agriculture 100×50 km, 1:200.000, 1990–2017.

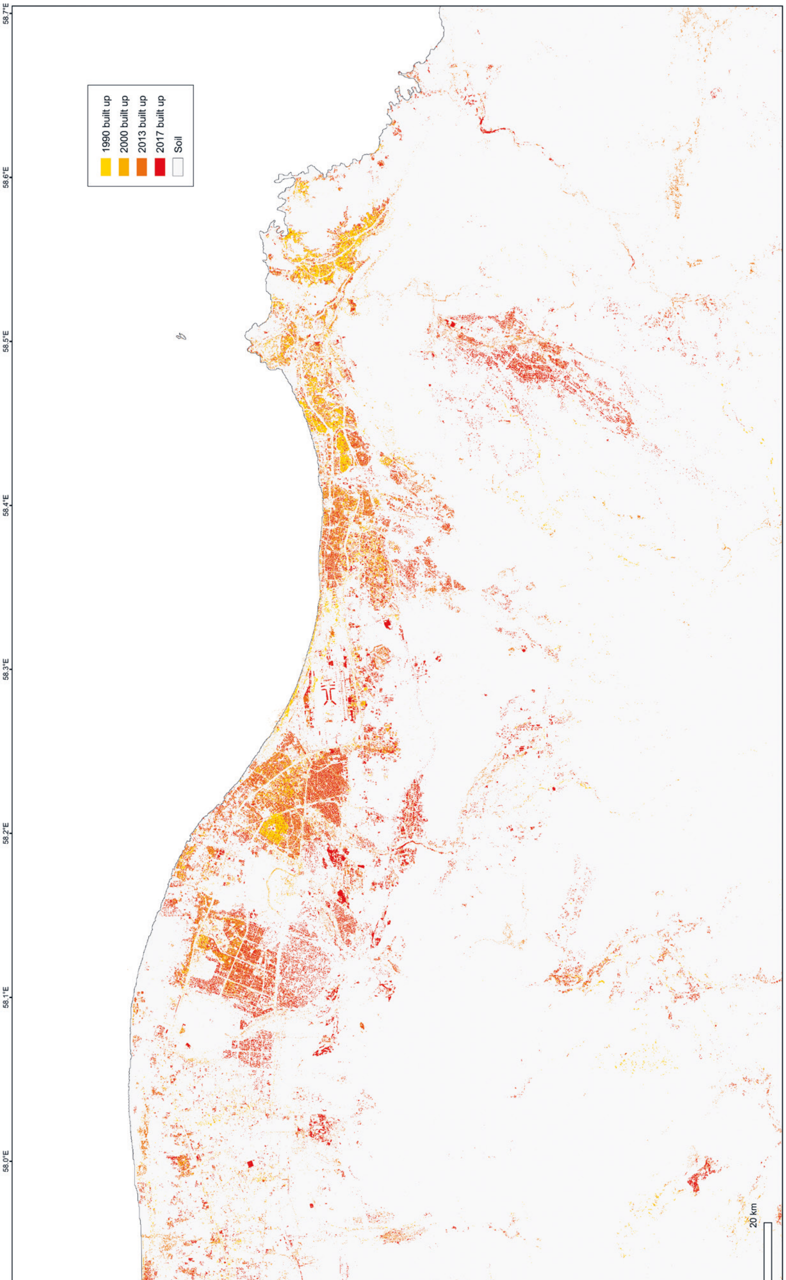


FIGURE 58

Regional Map of MCA 1 – Built-up Area 100×50 km, 1:200.000, 1990–2017.

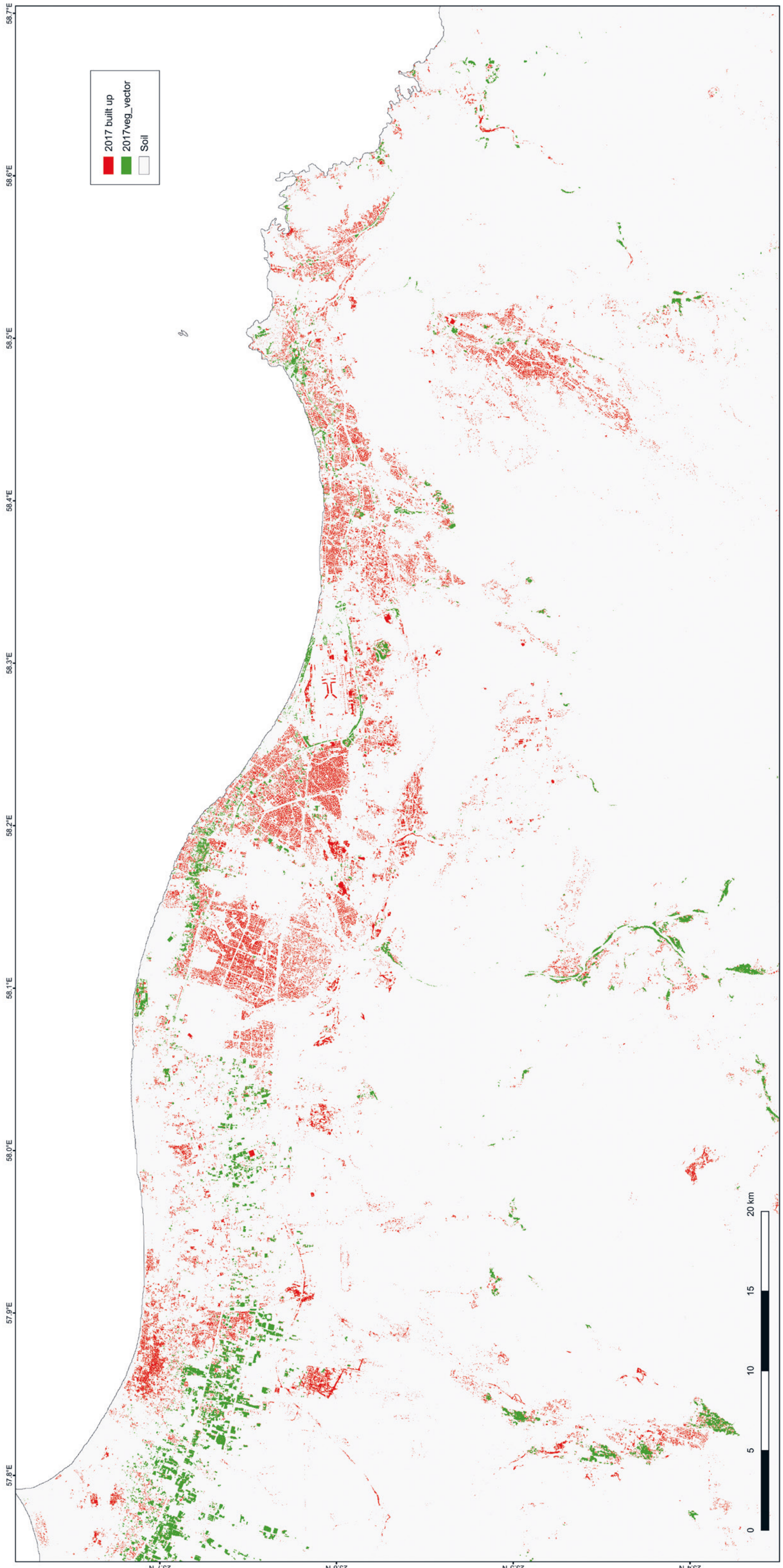


FIGURE 59
Regional Map of MCA 1 – Agriculture/Built-up Area 100×50 km, 1:200.000, 2017.

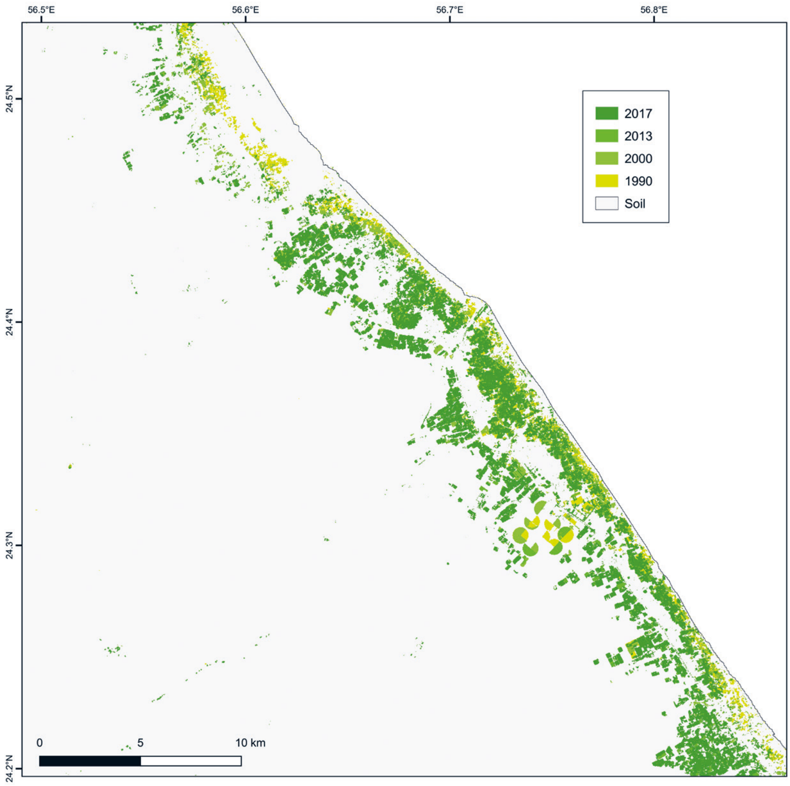


FIGURE 60
Regional Map of MCA 2 – Agriculture 40×40 km, 1:200.000, 1990–2017.

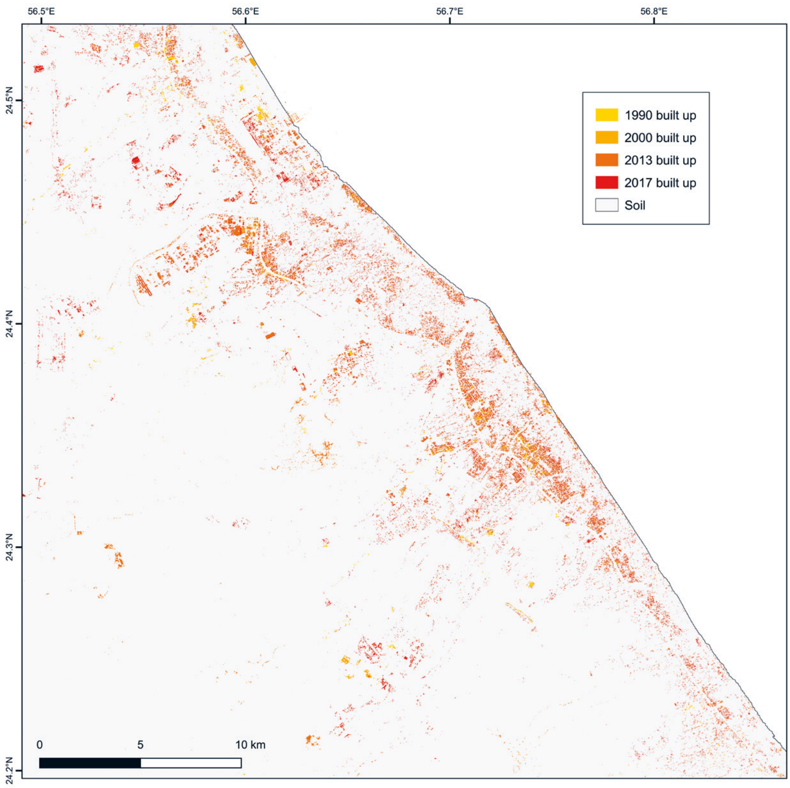


FIGURE 61
Regional Map of MCA 2 – Built-up Area 40×40 km, 1:200.000, 1990–2017.

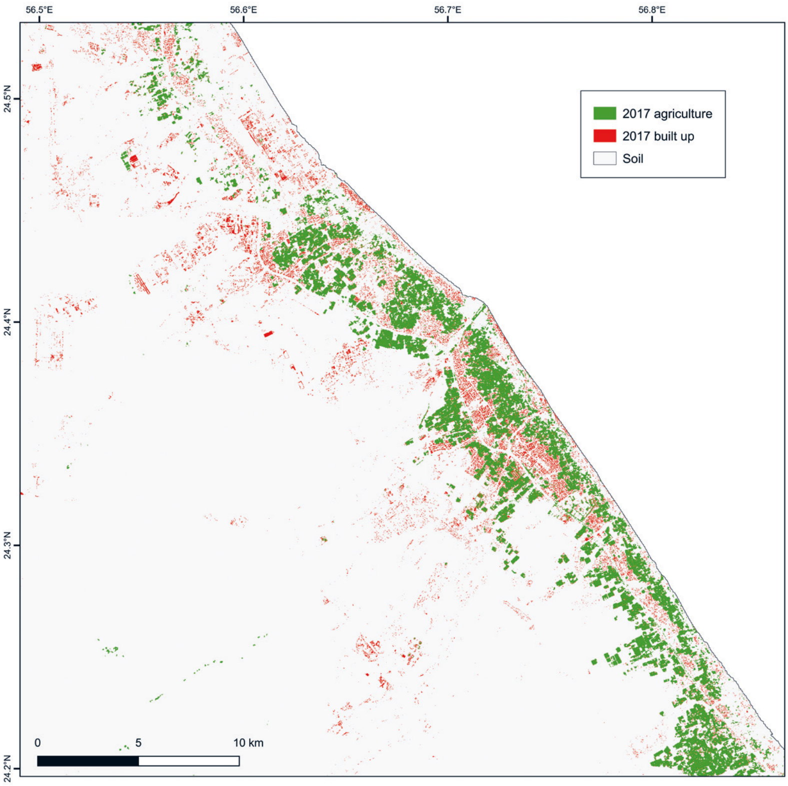


FIGURE 62
Regional Map of MCA 2 – Agriculture/Built-up Area 40×40 km, 1:200.000, 1990–2017.

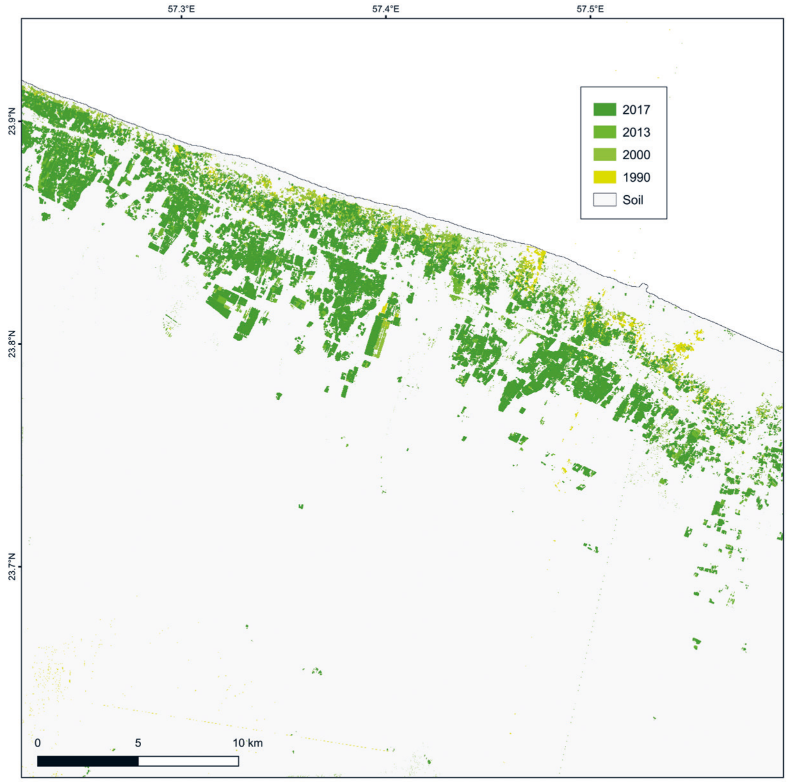


FIGURE 63
Regional Map of MCA 3 – Agriculture 40×40 km, 1:200.000, 1990–2017.

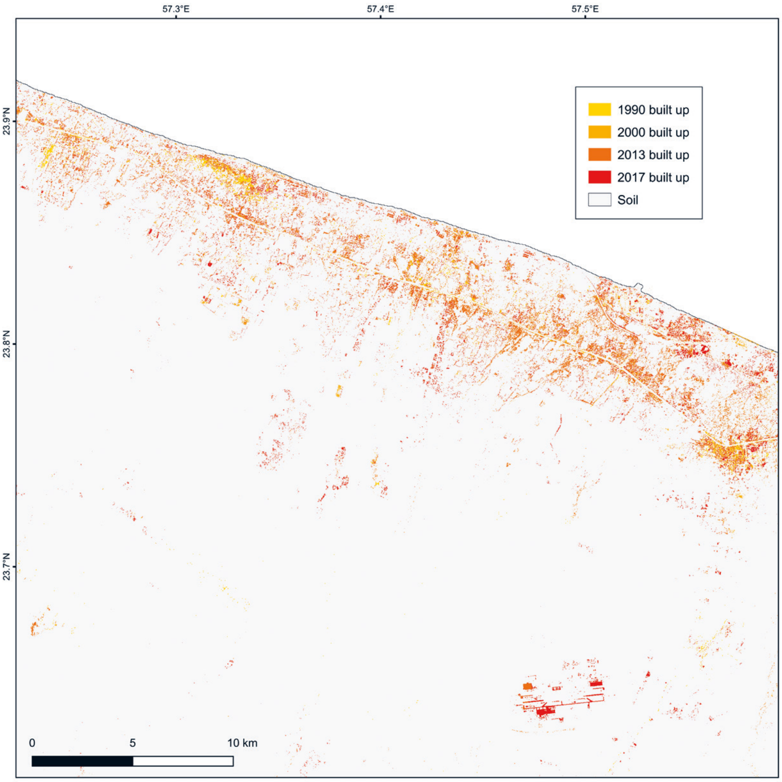


FIGURE 64
Regional Map of MCA 3 – Built-up Area 40×40 km, 1:200.000, 1990–2017.

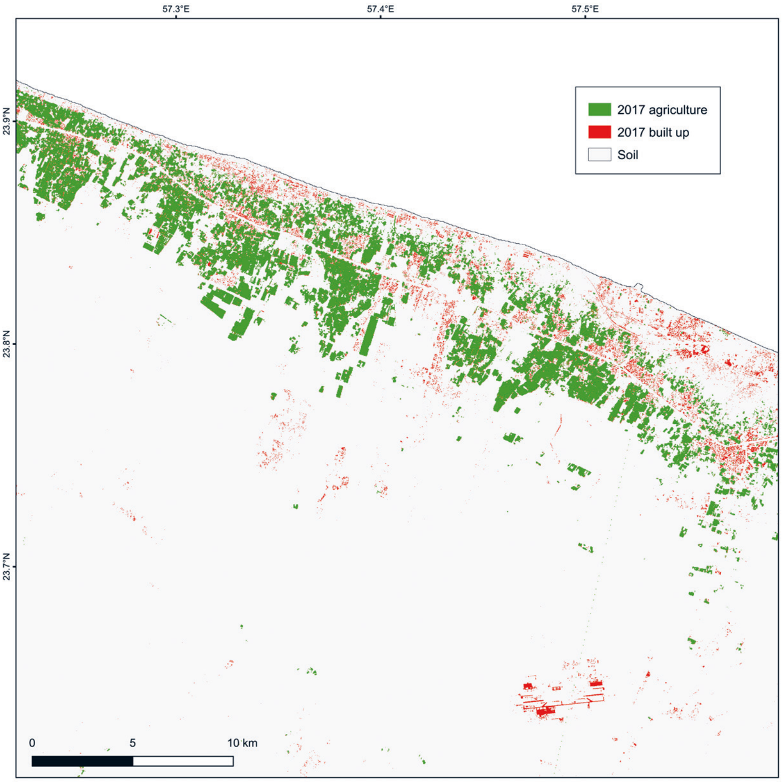


FIGURE 65
Regional Map of MCA 3 – Agriculture/Built-up Area 40×40 km, 1:200.000, 1990–2017.

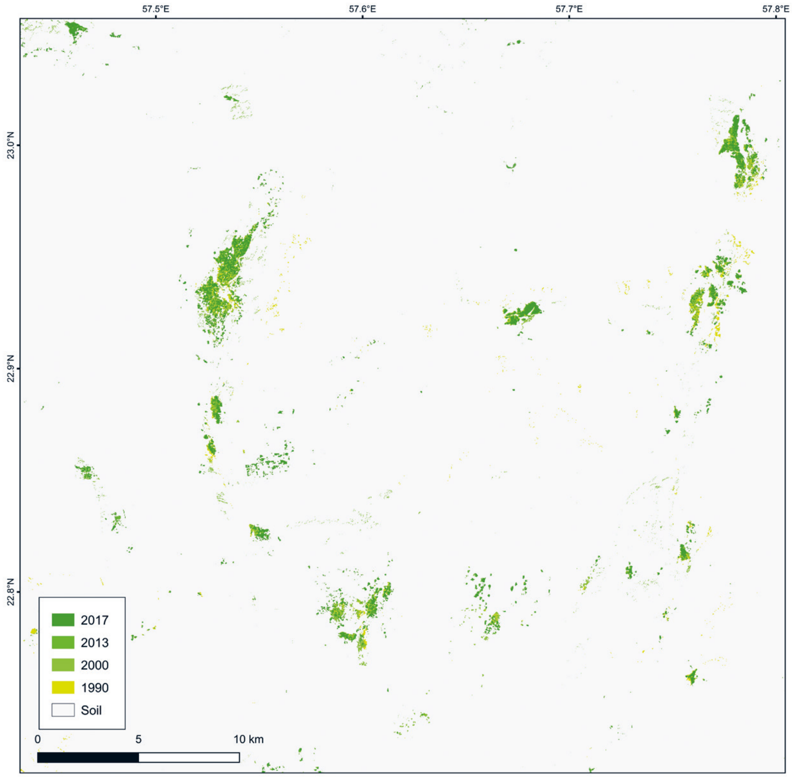


FIGURE 66
Regional Map of NIZ – Agriculture 40×40 km, 1:200.000, 1990–2017.

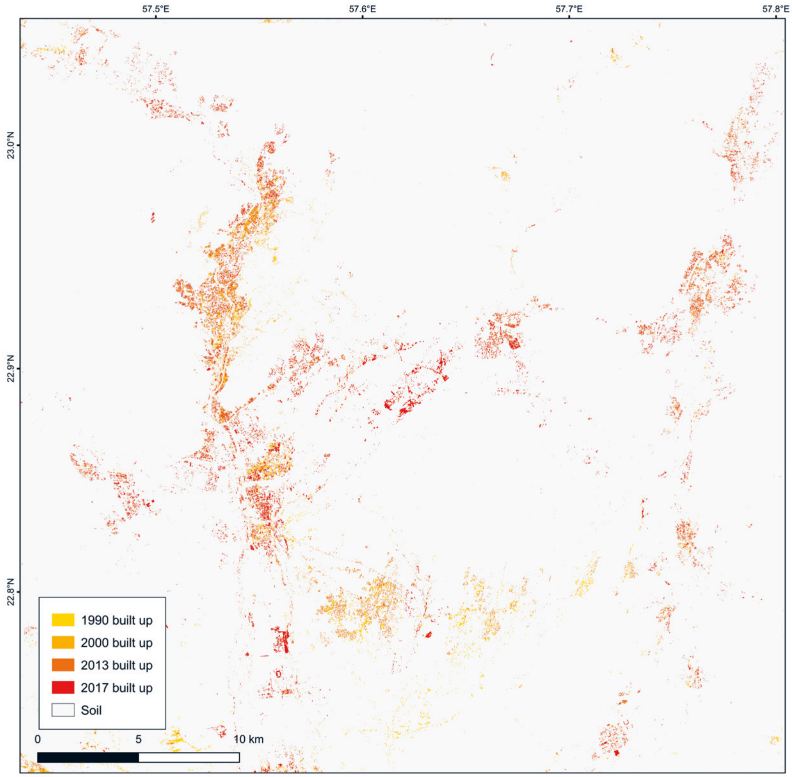


FIGURE 67
Regional Map of NIZ – Built-up Area 40×40 km, 1:200.000, 1990–2017.

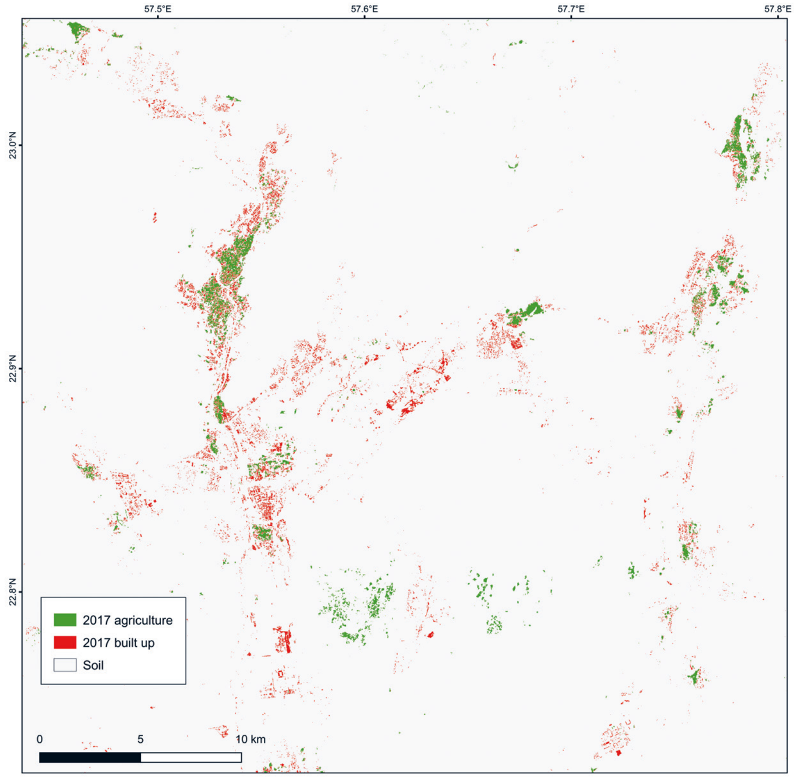


FIGURE 68
Regional Map of NIZ – Agriculture/Built-up Area 40×40 km, 1:200.000, 1990–2017.

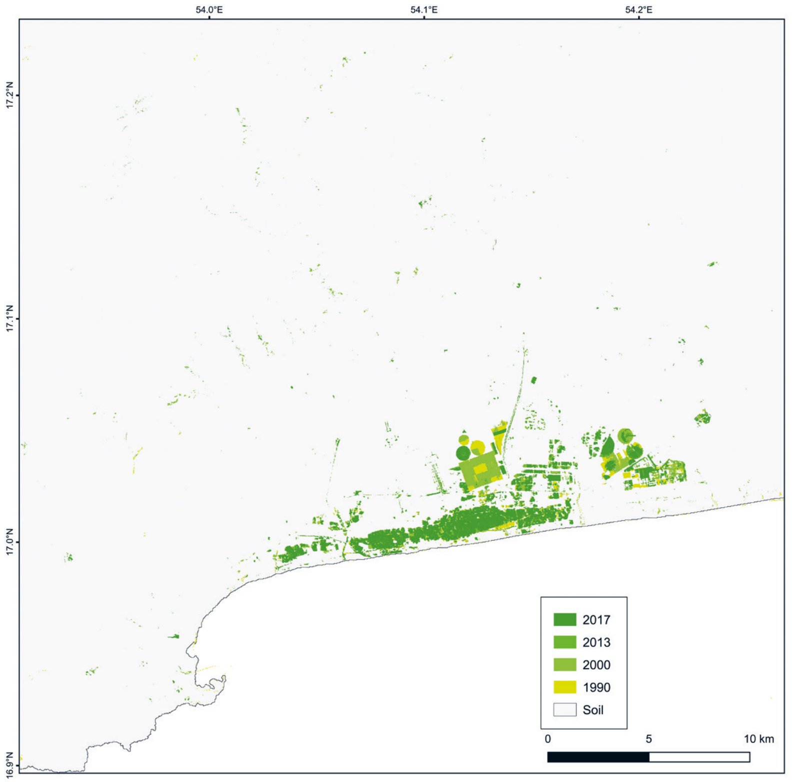


FIGURE 69
Regional Map of SAL – Agriculture 40×40 km, 1:200.000, 1990–2017.

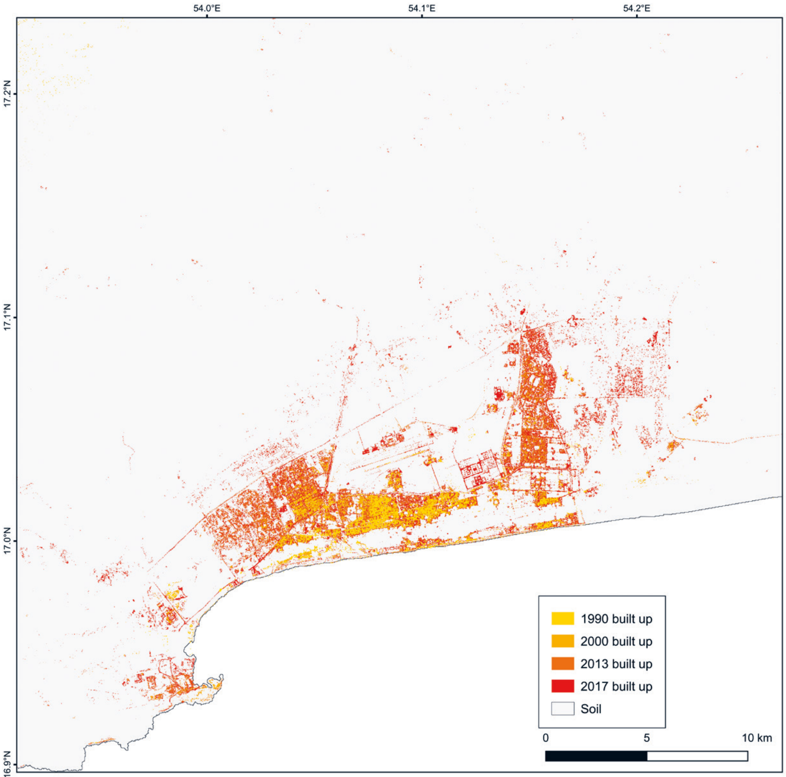


FIGURE 70
Regional Map of SAL – Built-up Area 40×40 km, 1:200.000, 1990–2017.

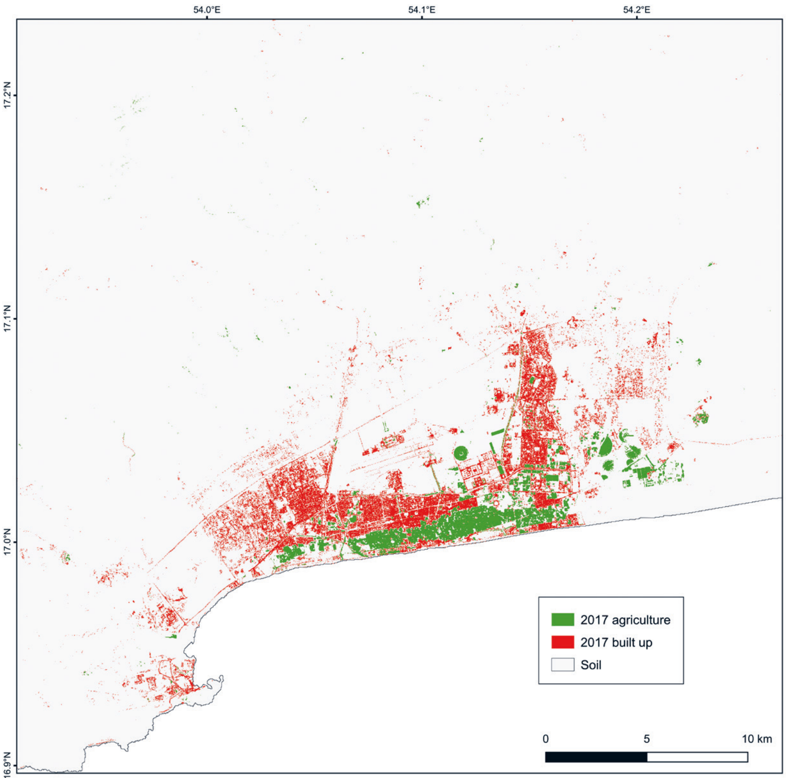


FIGURE 71
Regional Map of SAL – Agriculture/Built-up Area 40×40 km, 1:200.000, 1990–2017.

LOCAL SCALE

The 18 local case studies are located within the five regional case studies examined above. These local samples serve to describe particular urbanisation phenomena that stand for the dynamic and hybrid form of land use transformation in Oman in general. Each sample has a size of 2×2 km and is shown as a set of three maps: the temporal development of agricultural land uses for 1990–2017; built-up land uses for 1990–2017; and juxtaposition of agricultural and built-up land uses in 2017. This last set has been statistically analysed to classify space species found in the samples. These space species have been defined as logical combinations of Compact-Scattered shapes (C-S); Short-Long peripheries (S-L); and Small-Large areas (S-L):

CSS; CSL; CLL; CLS; SSS; SSL; SLS; SLL.

These space species are analysed using Shannon's diversity model. Shannon's diversity is calculated based on the eight possible spatial species defined hereafter. The maximum diversity *Hmax* value is constant at 2.08, while the measured diversity is indicated by *H*. The *Equitability* compares maximum to measured diversity. This diversity is discussed against the identified land use morphology and the historic land use transformation of the sample.

The local map of MCA 1a sample is located in Muscat Capital Area in the Al Khoud neighbourhood. This area has been surveyed in detail for the Urban Oman research project [329] as well as for the agent-based models to represent settlement economics. [330] This area is an example of recent urban growth and expansion. It serves as a special case study to verify the analytical findings of the mapping and to ground truth the spatial diversity concept of this thesis on the basis of sound empirical material. The left map shows that there was very little agricultural activity on the site, mainly scattered date palms along the wadi. The middle map shows that the building activity started from scratch in the mid 2000s, increased by the mid 2010s but has not yet reached completion. The built-up area is composed of uniform features of similar size (SEE FIGURE 72). These findings correlate with the previous studies and agent-based simulations. The right map reveals that the tiny agricultural activity is spatially segregated and functionally disconnected from the

329 Nebel and von Richthofen, Aurel, *Urban Oman – Challenges, Trends and Perspectives*.

330 Heim et al., "On the Process and Economics of Land Settlement in Oman: Mathematical Modeling and Reasoning in Urban Planning and Design."

urban development. The Shannon diversity calculated for the agricultural features is not significant because of the low feature count (SEE TABLE 9). The low spatial diversity merits mention as new developments in Muscat Capital Area programmatically exclude agriculture. The Shannon diversity calculated for the built-up features comprises 330 individual space species. They fall into four categories: CSS (compact short small), SSS (scattered short small), SLS (scattered long small) and SLL (scattered long large), wherein CSS forms the largest group (SEE TABLE 10). The groups of scattered space species reflect the low-density character of the neighbourhood, where informal additions and the use of interstitial spaces between buildings are common. The Equitability (gap between *H* and *Hmax*) of the sample is relatively high.

The local map of MCA 1b sample is also located in Muscat Capital Area, further north in reference to the MCA 1a sample. The left map shows a significant decline in agricultural activity on the site. The agricultural land use has been reduced to a quarter of its former size, while the built-up area significantly encroached upon this land as visible in the left map. The agricultural space transformed from a large spatial continuity to scattered small spaces (SEE FIGURE 73). This is visible in the Shannon diversity for the agricultural set where the CSS (compact short small) and SSS (scattered short small) spaces form the majority (SEE TABLE 11), and while the built-up space is increasing it is not less fragmented (SEE TABLE 12). The Shannon diversity shows that all spaces are either compact and small or scattered. The Equitability of the sample for both agricultural and urban sets is average. This might be due to the fact that the transition from rural to urban, as recorded by remote sensing, is not complete and thus exhibits a temporarily average diversity for both sets.

The local map of MCA 1c sample is located on the western side of Muscat Capital Area. The left map shows that agricultural activity was largely absent on the site. The built-up area expanded in the 2000s in the northern part of the set and in the 2010s in the southern part, as visible in the central map (SEE FIGURE 74). The Shannon diversity for the agricultural set features only a few samples, all in the CSS (compact short small) and SSS (scattered short small) spaces (SEE TABLE 13). The built-up space increases dramatically and in fragmented fashion similar to the MCA 1a set. The Shannon diversity shows that all spaces are either compact and small or scattered, with CSS, SSS and SLL predominant (SEE TABLE 14). The Equitability of the sample for both agricultural and urban sets is relatively high.

The local map of MCA 1d sample is located in the neighbourhood of Al Qurm in Muscat Capital Area, the location of a very important mangrove forest. The left map shows a decline in mangrove area. While not an agricultural space per se, the mangrove forest performs important ecosystem services for the adjacent urban fabric such as being a bio-diversity hot spot, important coastal protector, water purification area and improver of the local micro-climate. The built-up area significantly expanded, as visible in the central map. While the mangrove forest is still intact it suffers from increased porosity on the edges (SEE FIGURE 75). This is visible in the Shannon diversity where SLL (scattered long large) spaces are present next to small and compact ones (SEE TABLE 15). The built-up space is highly fragmented in this site (SEE TABLE 16). The Shannon diversity shows that all spaces are either compact and small or scattered, as is typical for a neighbourhood with predominant villa construction. The Equitability of the sample sets is lower than average.

The local map of MCA 1e sample is located in the north of Muscat Capital Area. The left map shows that the previously sparse agricultural activity has declined significantly. The built-up area exploded in the 2000s and in the 2010s, as visible in the central map. The composition map to the right shows that both residential and agricultural spaces are segregated (SEE FIGURE 76). The Shannon diversity for the agricultural set features only a few samples that are all CSS (compact short small) and SSS (scattered short small) spaces (SEE TABLE 17). The built-up space increases similarly to the MCA 1a and MCA 1c sets. The Shannon diversity for the built-up spaces shows that all spaces are either compact and small or scattered and large with CSS and SLL as predominant spaces (SEE TABLE 18). The Equitability of the sample sets is average low.

The next set of maps for Muscat Capital Area (MCA 1f; MCA 2a,b,c; MCA 3a,b) will be discussed together as these exhibit similar features and trends (SEE FIGURES 77–82 AND TABLES 19–30).

The local map of MCA 1f shows that agricultural spaces are stagnating in this set. One large agricultural feature resists urban encroachment (SEE FIGURE 77). The built-up space is developing very fast with an acceleration over the last decade. Spaces are predominantly compact and small or scattered and large (SEE TABLES 19–20). The Equitability of the sample sets is average.

The local map of MCA 2a is located along the Al Batinah plain outside of Muscat Capital Area. This former agricultural land shows a dramatic decline in agricultural spaces, while the built-up space is developing very fast with an acceleration over the last decade. Agricultural spaces retract over time, while the built-up spaces expand. These initially encroached upon the agricultural spaces, but they now also expand into previously unused gravel deserts (SEE FIGURE 78). The built-up spaces are predominantly compact and small or scattered and large just as in the urban expansion area of Muscat Capital Area (SEE TABLES 21–22). The Equitability of the sample sets is slightly above average.

The local map of MCA 2b is also located along the Al Batinah plain. It shows a decline in agricultural land, mainly abandoned date plantations. This stretch is close to the coast and suffers from over-extraction of fresh-water aquifers and salt-water infiltration that renders the ground unsuitable for agriculture. One can also see that the urban development increases and that more and more space is built up in pockets within the former agricultural land. The erosion process of agricultural space is ongoing (SEE FIGURE 79). The Equitability of agricultural spaces is thus low, while the built-up spaces profit from this with an average high value (SEE TABLES 23–24).

The local map of MCA 2c shows a dense agricultural region along the Al Batinah coast. This oasis settlement has also suffered significant losses recently. Small-scale built-up spaces appear in between the oasis settlement and contribute to agricultural space loss (SEE FIGURE 80). For the moment both space sets display relative stable spatial patterns: The agricultural space consists of a few scattered large areas next to compact small ones, while the built-up spaces are predominantly compact and small (SEE TABLES 25–26). The Equitability of the sample sets is very low.

The local map of MCA 3a, located in the northern Al Batinah region, shows how urbanisation along main road networks erodes the agricultural spaces. This set shows a steady decline since the 1990s and overall loss of 40% of agricultural spaces. This goes along with a fragmentation and isolation of these spaces. The built-up space is developing very fast with an acceleration over the last decade and radial sprawl originating from the road infrastructure (SEE FIGURE 81). The Equitability of the sample sets is average as the transformation process is ongoing (SEE TABLES 27–28).

A similar process can be observed within the local map of MCA 3 b. Infrastructure triggers urban development encroaching upon agricultural land use (SEE FIGURE 82). The Equitability of the sample agricultural set is low which in return benefits the urban space whose Equitability is higher than average (SEE TABLES 29–30).

The next set of maps examines the Omani interior around the oasis town of Nizwa (NIZ a, b, c as represented in the figures 83–85 and tables 31–36). The local map of NIZ a shows how small oasis settlements gradually decline and how urban sprawl massively changes the landscape of the Omani interior as visible on the centre and right maps (SEE FIGURE 83). The agricultural spaces are either compact and small or scattered and large with an Equitably slightly above average (SEE TABLES 31–32). The urban spaces are far more numerous and a bit more variegated. The Equitability is average. It is important to note that the transformation process from rural to urban is still ongoing, just as in Muscat Capital Area, and that the expansion is not restricted to the former agricultural spaces, but gradually includes expansion into the gravel deserts.

The local map of NIZ b shows dramatically porous agricultural spaces. The pockets of porosity increased recently and have been filled with built-up spaces. While the agricultural space is confined to specific irrigated areas, the built-up space scatters across the set (SEE FIGURE 84 AND TABLES 33–34). The Equitability of the agricultural space is low, while that of the built-up space is average. This indicates that the process is not completed and that spatial diversity in the urban set comes at the expense of the agricultural set. All the above applies to the local map of NIZ c that actually shows the town of Nizwa itself set within an extended oasis. The agricultural space became extremely porous to the point of showing mostly compact short small features. The built-up space transgressed and intertwined with all parts of the agricultural land. The result is a scattered urban-agricultural carpet. The Equitability of both sets is average but equilibrated (SEE FIGURE 85 AND TABLES 35–36). Notwithstanding the radical transformation of Nizwa from a compact town with extensive oasis agriculture into a scattered rural-urban carpet the mix of agricultural to built-up spaces identified in the local map of NIZ c is optimal.

The following maps of Salalah are described together (SAL A, B, C AS REPRESENTED IN THE FIGURES 86–88 AND TABLES 37–42). The local map of SAL a shows how large areas of irrigated former plantation land were converted into urban land. All that remains is a circular industrially irrigated field next to an emerging urban settlement (SEE FIGURE 86). The spatial diversity of both sets is low average (SEE TABLES 37–38).

The local map of SAL b shows the extreme densification of urban spaces and the gradual erosion of the few agricultural land uses remaining in this map (SEE FIGURE 87). The urban spaces fall into two categories: Compact short small (CSS) and scattered short small (SSS). The Equitability of the urban set is low (SEE TABLES 39–40).

The last map of Salalah exemplifies the conflict of land uses apparent in this part of Oman. Due to the seasonal rainfall in this region in the monsoon months of July and August agriculture and settlement patterns have evolved closely together (SEE FIGURE 88). The spatial diversity has been reduced in both sets due to an ongoing process of densification and consolidation. The predominant spaces are compact short small (CSS) and scattered short small (SSS). These spaces offer little potential for any other use than small scale sub-urban (SEE TABLES 41–42). The Equitability is low average for both sets.

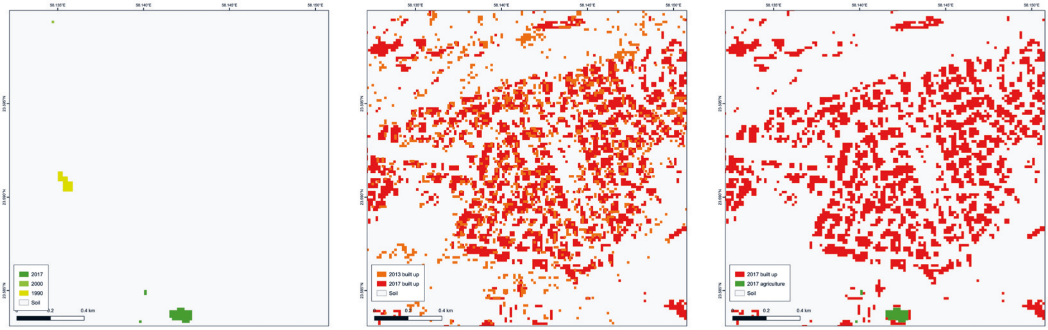


FIGURE 72
Local map of MCA 1a Agriculture/Built-up Area 2×2 km, 1:10.000, 1990–2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	H MAX	EQUITABILITY
CSS	2	0,67	-0,41	-0,27	**0,64**	2,08	**0,31**
CSL							
CLL							
CLS							
SSS							
SSL							
SLS							
SLL	1	0,33	-1,10	-0,37			

SPECIES	INDIVIDUALS
8	3

TABLE 9
Shannon Diversity calculated for the local map of MCA 1a Agriculture 2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	177	0,54	-0,62	-0,33	**1,11**	2,08	**0,54**
CSL							
CLL							
CLS	1	0,00	-5,80	-0,02			
SSS	43	0,13	-2,04	-0,27			
SSL	1	0,00	-5,80	-0,02			
SLS	12	0,04	-3,31	-0,12			
SLL	96	0,29	-1,23	-0,36			

SPECIES	INDIVIDUALS
8	330

TABLE 10
Shannon Diversity calculated for the local map of MCA 1a Built-up 2017.

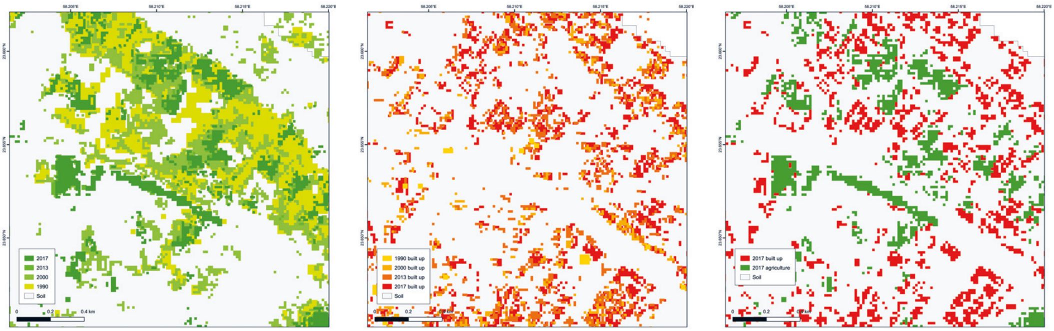


FIGURE 73
Local map of MCA 1b Agriculture/Built-up Area 2×2 km, 1:10.000, 1990–2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	137	0,69	-0,37	-0,25	**0,90**	2,08	**0,43**
CSL							
CLL							
CLS	1	0,01	-5,29	-0,03			
SSS	24	0,12	-2,11	-0,26			
SSL							
SLS	3	0,02	-4,19	-0,06			
SLL	33	0,17	-1,79	-0,30			

SPECIES	INDIVIDUALS
8	198

TABLE 11
Shannon Diversity calculated for the local map of MCA 1b Agriculture 2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	267	0,63	-0,46	-0,29	**0,96**	2,08	**0,46**
CSL	0						
CLL	0						
CLS	0						
SSS	27	0,06	-2,75	-0,18			
SSL	5	0,01	-4,43	-0,05			
SLS	11	0,03	-3,64	-0,10			
SLL	111	0,26	-1,33	-0,35			

SPECIES	INDIVIDUALS
8	421

TABLE 12
Shannon Diversity calculated for the local map of MCA 1b Built-up Area 2017.

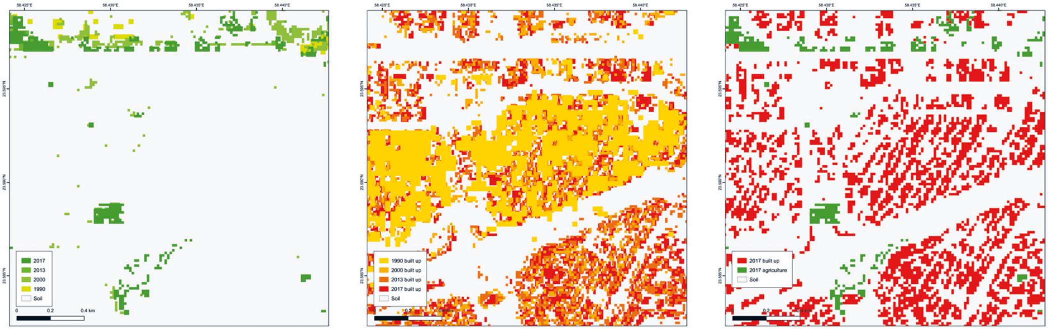


FIGURE 74
Local map of MCA 1c Agriculture/Built-up Area 2×2 km, 1:10.000, 1990–2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	41	0,60	-0,51	-0,31	**1,15**	2,08	**0,55**
CSL	0						
CLL	0						
CLS	0						
SSS	10	0,15	-1,92	-0,28			
SSL	2	0,03	-3,53	-0,10			
SLS	4	0,06	-2,83	-0,17			
SLL	11	0,16	-1,82	-0,29			

SPECIES	INDIVIDUALS
8	68

TABLE 13
Shannon Diversity calculated for the local map of MCA 1c Agriculture 2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	199	0,53	-0,64	-0,34	**1,21**	2,08	**0,58**
CSL	0						
CLL	1	0,00	-5,93	-0,02			
CLS	2	0,01	-5,24	-0,03			
SSS	62	0,16	-1,81	-0,30			
SSL	7	0,02	-3,99	-0,07			
SLS	12	0,03	-3,45	-0,11			
SLL	95	0,25	-1,38	-0,35			

SPECIES	INDIVIDUALS
8	378

TABLE 14
Shannon Diversity calculated for the local map of MCA 1c Built-up 2017.

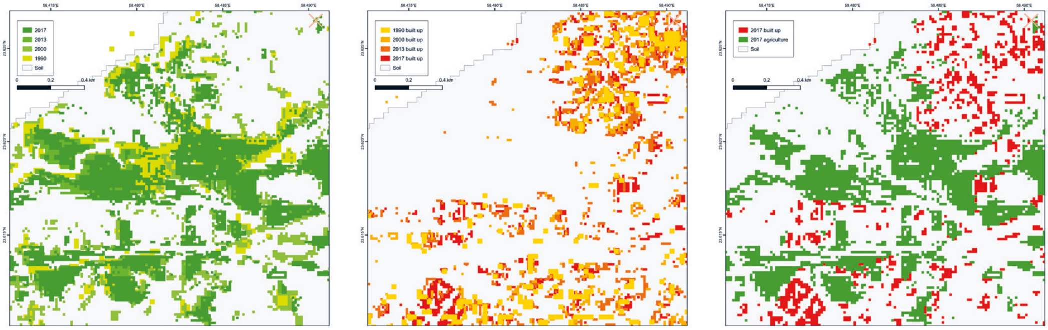


FIGURE 75
Local map of MCA 1d Agriculture/Built-up Area 2×2 km, 1:10.000, 1990–2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	146	0,72	-0,32	-0,23	**0,87**	2,08	**0,42**
CSL	0						
CLL	0						
CLS	0						
SSS	24	0,12	-2,13	-0,25			
SSL	0						
SLS	9	0,04	-3,11	-0,14			
SLL	23	0,11	-2,17	-0,25			

SPECIES	INDIVIDUALS
8	202

TABLE 15
Shannon Diversity calculated for the local map of MCA 1d Agriculture 2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	139	0,60	-0,51	-0,31	**1,03**	2,08	**0,49**
CSL	0						
CLL	1	0,00	-5,45	-0,02			
CLS	1	0,00	-5,45	-0,02			
SSS	20	0,09	-2,45	-0,21			
SSL	1	0,00	-5,45	-0,02			
SLS	5	0,02	-3,84	-0,08			
SLL	65	0,28	-1,27	-0,36			

SPECIES	INDIVIDUALS
8	232

TABLE 16
Shannon Diversity calculated for the local map of MCA 1d Built-up 2017.

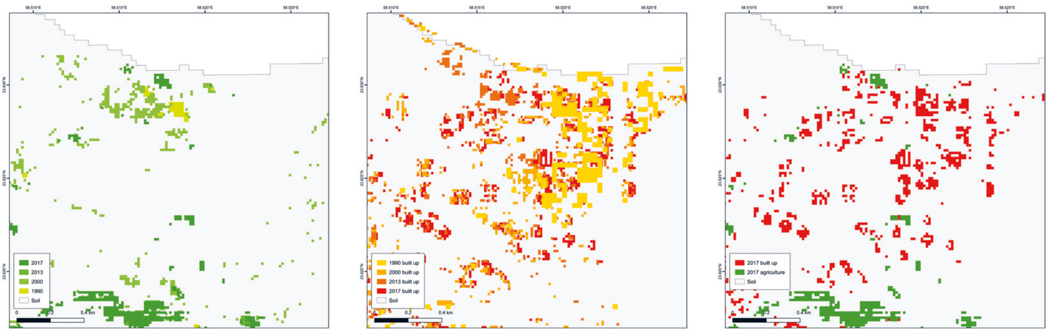


FIGURE 76
Local map of MCA 1e Agriculture/Built-up Area 2×2 km, 1:10.000, 1990–2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	30	0,71	-0,34	-0,24	**0,87**	2,08	**0,42**
CSL	0						
CLL	0						
CLS	0						
SSS	3	0,07	-2,64	-0,19			
SSL	0						
SLS	2	0,05	-3,04	-0,14			
SLL	7	0,17	-1,79	-0,30			

SPECIES	INDIVIDUALS
8	42

TABLE 17
Shannon Diversity calculated for the local map of MCA 1e Agriculture 2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	125	0,64	-0,45	-0,29	**0,87**	2,08	**0,42**
CSL	0						
CLL	0						
CLS	0						
SSS	4	0,02	-3,89	-0,08			
SSL	0						
SLS	9	0,05	-3,08	-0,14			
SLL	58	0,30	-1,22	-0,36			

SPECIES	INDIVIDUALS
8	196

TABLE 18
Shannon Diversity calculated for the local map of MCA 1e Built-up 2017.

FIGURE 77
Local map of MCA 1f Agriculture/Built-up Area 2×2 km, 1:10.000, 1990–2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	25	0,61	-0,49	-0,30	**1,16**	2,08	**0,56**
CSL	0						
CLL	0						
CLS	1	0,02	-3,71	-0,09			
SSS	6	0,15	-1,92	-0,28			
SSL	0						
SLS	5	0,12	-2,10	-0,26			
SLL	4	0,10	-2,33	-0,23			

SPECIES	INDIVIDUALS
8	41

TABLE 19
Shannon Diversity calculated for the local map of MCA 1f Agriculture 2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	199	0,66	-0,41	-0,27	**0,98**	2,08	**0,47**
CSL	0						
CLL	0						
CLS	2	0,01	-5,01	-0,03			
SSS	22	0,07	-2,61	-0,19			
SSL	0						
SLS	17	0,06	-2,87	-0,16			
SLL	60	0,20	-1,61	-0,32			

SPECIES	INDIVIDUALS
8	300

TABLE 20
Shannon Diversity calculated for the local map of MCA 1f Built-up 2017.

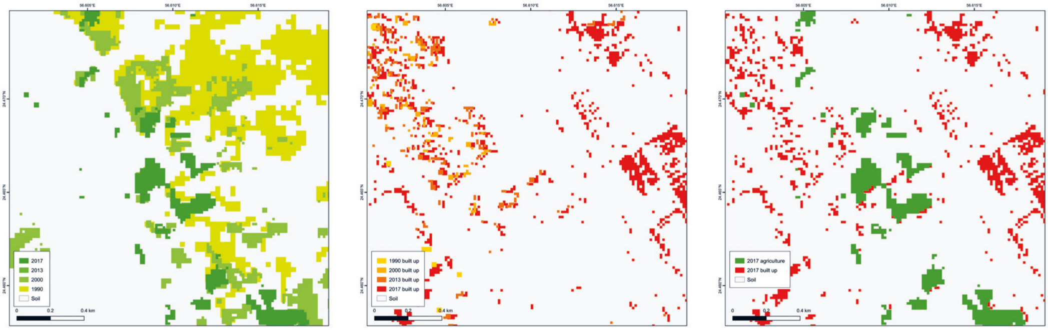


FIGURE 78
Local map of MCA 2a Agriculture/Built-up Area 2×2 km, 1:10.000, 1990–2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	18	0,58	-0,54	-0,32	**1,13**	2,08	**0,54**
CSL	0						
CLL	0						
CLS	2	0,06	-2,74	-0,18			
SSS	2	0,06	-2,74	-0,18			
SSL	0						
SLS	1	0,03	-3,43	-0,11			
SLL	8	0,26	-1,35	-0,35			

SPECIES	INDIVIDUALS
8	31

TABLE 21
Shannon Diversity calculated for the local map of MCA 2a Agriculture 2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	206	0,60	-0,50	-0,30	**1,09**	2,08	**0,52**
CSL	0						
CLL	0						
CLS	1	0,00	-5,83	-0,02			
SSS	31	0,09	-2,40	-0,22			
SSL	0						
SLS	32	0,09	-2,37	-0,22			
SLL	71	0,21	-1,57	-0,33			

SPECIES	INDIVIDUALS
8	341

TABLE 22
Shannon Diversity calculated for the local map of MCA 2a Built-up 2017.

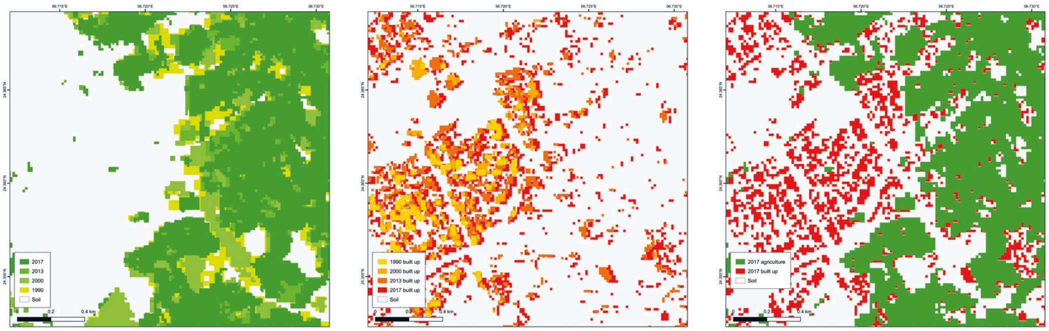


FIGURE 79
Local map of MCA 2b Agriculture/Built-up Area 2×2 km, 1:10.000, 1990–2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	28	0,76	-0,28	-0,21	**0,76**	2,08	**0,37**
CSL	0						
CLL	0						
CLS	0						
SSS	6	0,16	-1,82	-0,29			
SSL	0						
SLS	1	0,03	-3,61	-0,10			
SLL	2	0,05	-2,92	-0,16			

SPECIES	INDIVIDUALS
8	37

TABLE 23
Shannon Diversity calculated for the local map of MCA 2b Agriculture 2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	314	0,59	-0,53	-0,31	**1,07**	2,08	**0,51**
CSL	0						
CLL	1	0,00	-6,28	-0,01			
CLS	0						
SSS	87	0,16	-1,81	-0,30			
SSL	9	0,02	-4,08	-0,07			
SLS	6	0,01	-4,48	-0,05			
SLL	115	0,22	-1,53	-0,33			

SPECIES	INDIVIDUALS
8	532

TABLE 24
Shannon Diversity calculated for the local map of MCA 2b Built-up 2017.

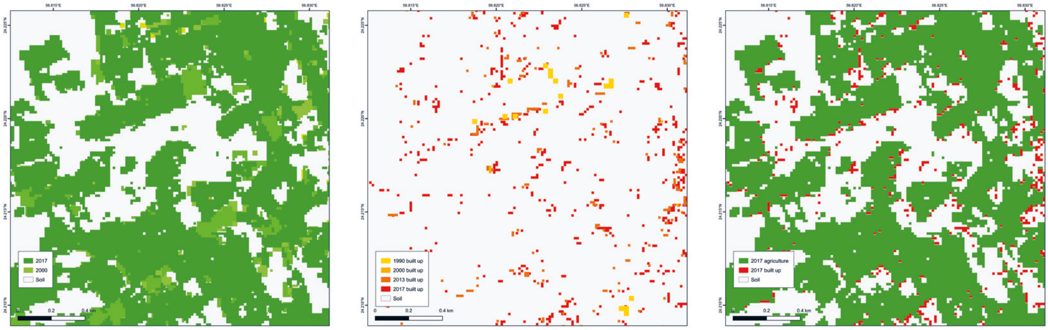


FIGURE 80
Local map of MCA 2c Agriculture/Built-up Area 2×2 km, 1:10.000, 1990–2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	24	0,65	-0,43	-0,28	**0,80**	2,08	**0,38**
CSL	0						
CLL	0						
CLS	0						
SSS	11	0,30	-1,21	-0,36			
SSL	0						
SLS	0						
SLL	2	0,05	-2,92	-0,16			

SPECIES	INDIVIDUALS
8	37

TABLE 25
Shannon Diversity calculated for the local map of MCA 2c Agriculture 2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	207	0,65	-0,43	-0,28	**0,67**	2,08	**0,32**
CSL	0						
CLL	0						
CLS	0						
SSS	1	0,00	-5,77	-0,02			
SSL	0						
SLS	0						
SLL	111	0,35	-1,06	-0,37			

SPECIES	INDIVIDUALS
8	319

TABLE 26
Shannon Diversity calculated for the local map of MCA 2c Built-up 2017.

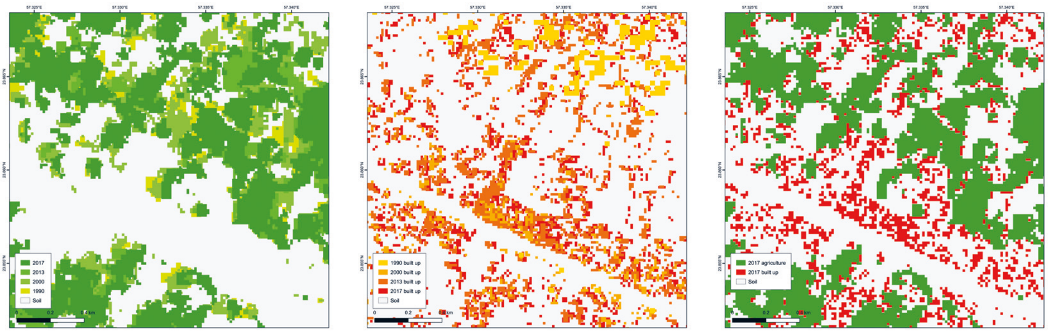


FIGURE 81
Local map of MCA 3a Agriculture/Built-up Area 2×2 km, 1:10.000, 1990–2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	44	0,64	-0,45	-0,29	**0,88**	2,08	**0,42**
CSL	0						
CLL	0						
CLS	0						
SSS	17	0,25	-1,40	-0,35			
SSL	0						
SLS	0						
SLL	8	0,12	-2,15	-0,25			

SPECIES	INDIVIDUALS
8	69

TABLE 27
Shannon Diversity calculated for the local map of MCA 3a Agriculture 2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	411	0,64	-0,45	-0,29	**0,97**	2,08	**0,46**
CSL	0						
CLL	2	0,00	-5,78	-0,02			
CLS	1	0,00	-6,47	-0,01			
SSS	60	0,09	-2,38	-0,22			
SSL	12	0,02	-3,99	-0,07			
SLS	1	0,00	-6,47	-0,01			
SLL	159	0,25	-1,40	-0,35			

SPECIES	INDIVIDUALS
8	646

TABLE 28
Shannon Diversity calculated for the local map of MCA 3a Built-up 2017.

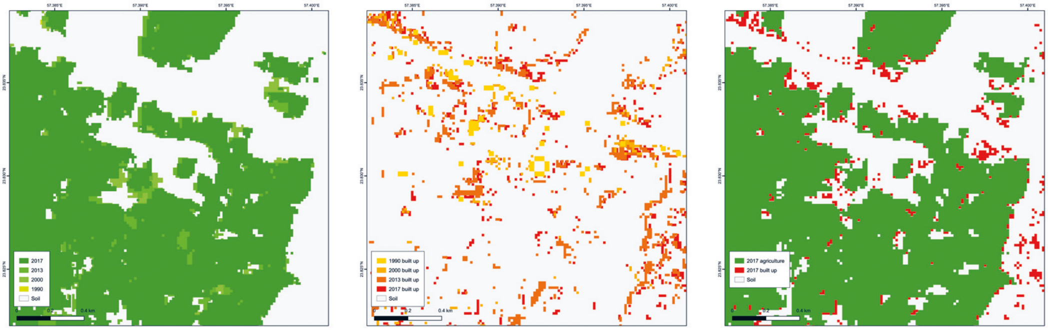


FIGURE 82
Local map of MCA 3b Agriculture/Built-up Area 2×2 km, 1:10.000, 1990–2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	10	0,63	-0,47	-0,29	**0,90**	2,08	**0,43**
CSL	0						
CLL	0						
CLS	0						
SSS	4	0,25	-1,39	-0,35			
SSL	0						
SLS	0						
SLL	2	0,13	-2,08	-0,26			

SPECIES	INDIVIDUALS
8	16

TABLE 29
Shannon Diversity calculated for the local map of MCA 3b Agriculture 2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	142	0,48	-0,73	-0,35	**1,40**	2,08	**0,68**
CSL	0						
CLL	8	0,03	-3,60	-0,10			
CLS	54	0,18	-1,69	-0,31			
SSS	27	0,09	-2,39	-0,22			
SSL	53	0,18	-1,71	-0,31			
SLS	0						
SLL	10	0,03	-3,38	-0,11			

SPECIES	INDIVIDUALS
8	294

TABLE 30
Shannon Diversity calculated for the local map of MCA 3b Built-up 2017.

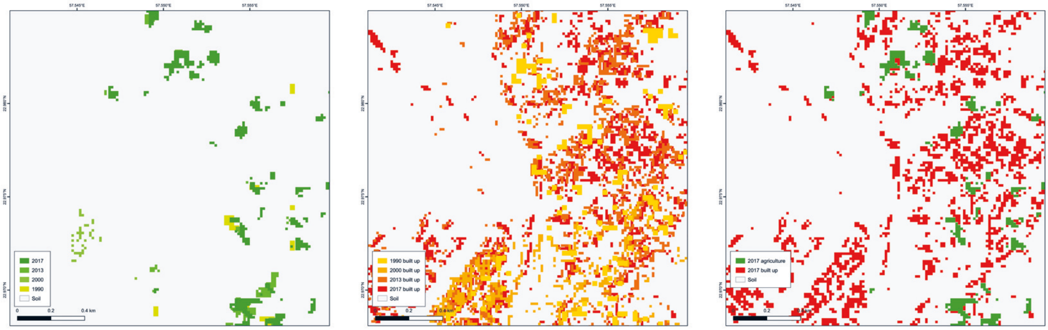


FIGURE 83
Local map of NIZ a Agriculture/Built-up Area 2×2 km, 1:10.000, 1990–2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	24	0,52	-0,65	-0,34	**1,11**	2,08	**0,54**
CSL	0						
CLL	0						
CLS	1	0,02	-3,83	-0,08			
SSS	5	0,11	-2,22	-0,24			
SSL	1	0,02	-3,83	-0,08			
SLS	0						
SLL	15	0,33	-1,12	-0,37			

SPECIES	INDIVIDUALS
8	46

TABLE 31
Shannon Diversity calculated for the local map of NIZ a Agriculture 2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	222	0,61	-0,50	-0,30	**1,01**	2,08	**0,49**
CSL	0						
CLL	0						
CLS	0						
SSS	50	0,14	-1,99	-0,27			
SSL	3	0,01	-4,80	-0,04			
SLS	5	0,01	-4,29	-0,06			
SLL	86	0,23	-1,45	-0,34			

SPECIES	INDIVIDUALS
8	366

TABLE 32
Shannon Diversity calculated for the local map of NIZ a Built-up 2017.

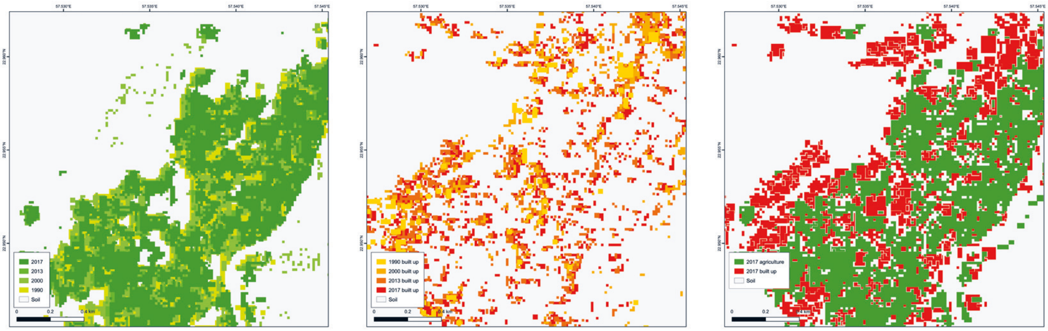


FIGURE 84
Local map of NIZ b Agriculture/Built-up Area 2×2 km, 1:10.000, 1990–2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	57	0,74	-0,30	-0,22	**0,81**	2,08	**0,39**
CSL	0						
CLL	0						
CLS	0						
SSS	12	0,16	-1,86	-0,29			
SSL	0						
SLS	2	0,03	-3,65	-0,09			
SLL	6	0,08	-2,55	-0,20			

SPECIES	INDIVIDUALS
8	77

TABLE 33
Shannon Diversity calculated for the local map of NIZ b Agriculture 2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	251	0,59	-0,53	-0,31	**1,04**	2,08	**0,50**
CSL	0						
CLL	0						
CLS	0						
SSS	55	0,13	-2,04	-0,26			
SSL	0						
SLS	15	0,04	-3,34	-0,12			
SLL	104	0,24	-1,41	-0,34			

SPECIES	INDIVIDUALS
8	425

TABLE 34
Shannon Diversity calculated for the local map of NIZ b Built-up 2017.

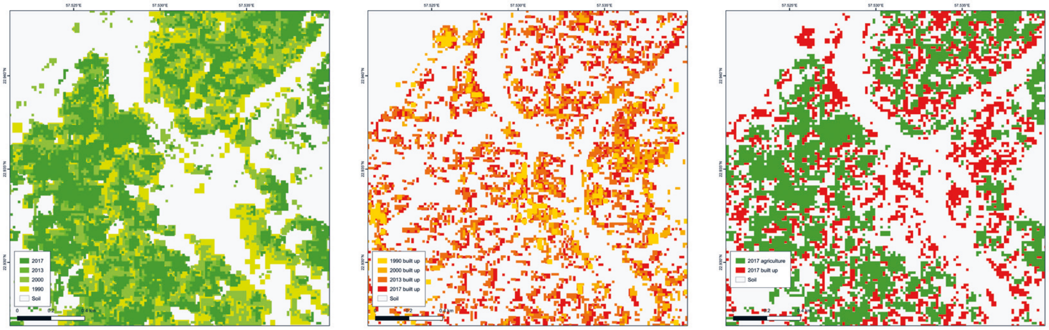


FIGURE 85

Local map of NIZ c Agriculture/Built-up Area 2×2 km, 1:10.000, 1990–2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	159	0,71	-0,34	-0,24	**0,90**	2,08	**0,43**
CSL	0						
CLL	0						
CLS	0						
SSS	25	0,11	-2,19	-0,24			
SSL	1	0,00	-5,41	-0,02			
SLS	7	0,03	-3,47	-0,11			
SLL	32	0,14	-1,95	-0,28			

SPECIES	INDIVIDUALS
8	224

TABLE 35

Shannon Diversity calculated for the local map of NIZ c Agriculture 2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	315	0,55	-0,59	-0,33	**1,09**	2,08	**0,53**
CSL	0						
CLL	0						
CLS	2	0,00	-5,65	-0,02			
SSS	115	0,20	-1,60	-0,32			
SSL	1	0,00	-6,34	-0,01			
SLS	12	0,02	-3,86	-0,08			
SLL	123	0,22	-1,53	-0,33			

SPECIES	INDIVIDUALS
8	568

TABLE 36

Shannon Diversity calculated for the local map of NIZ c Built-up 2017.

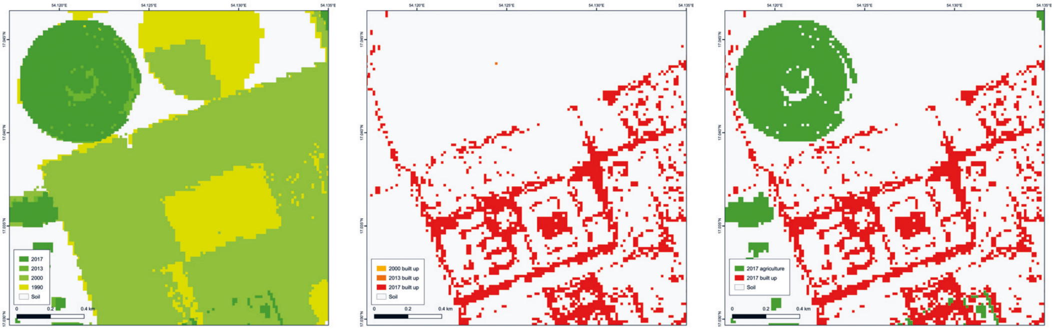


FIGURE 86
Local map of SAL a Agriculture/Built-up Area 2×2 km, 1:10.000, 1990–2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	16	0,73	-0,32	-0,23	**0,86**	2,08	**0,41**
CSL	0						
CLL	0						
CLS	0						
SSS	3	0,14	-1,99	-0,27			
SSL	0						
SLS	1	0,05	-3,09	-0,14			
SLL	2	0,09	-2,40	-0,22			

SPECIES	INDIVIDUALS
8	22

TABLE 37
Shannon Diversity calculated for the local map of SAL a Agriculture 2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	211	0,68	-0,38	-0,26	**0,93**	2,08	**0,45**
CSL	0						
CLL	0						
CLS	2	0,01	-5,04	-0,03			
SSS	58	0,19	-1,68	-0,31			
SSL	3	0,01	-4,64	-0,04			
SLS	2	0,01	-5,04	-0,03			
SLL	34	0,11	-2,21	-0,24			

SPECIES	INDIVIDUALS
8	310

TABLE 38
Shannon Diversity calculated for the local map of SAL Built-up 2017.

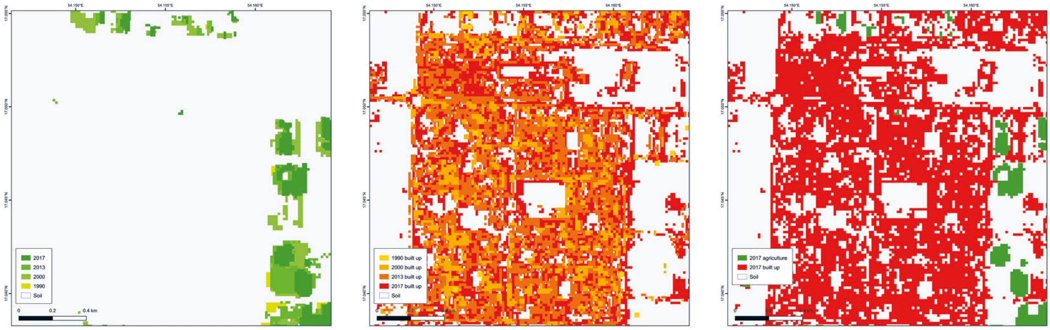


FIGURE 87
Local map of SAL b Agriculture/Built-up Area 2×2 km, 1:10.000, 1990–2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	13	0,62	-0,48	-0,30	**0,94**	2,08	**0,45**
CSL	0						
CLL	0						
CLS	0						
SSS	1	0,05	-3,04	-0,14			
SSL	0						
SLS	1	0,05	-3,04	-0,14			
SLL	6	0,29	-1,25	-0,36			

SPECIES	INDIVIDUALS
8	21

TABLE 39
Shannon Diversity calculated for the local map of SAL b Agriculture 2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	87	0,74	-0,30	-0,22	**0,71**	2,08	**0,34**
CSL	0						
CLL	0						
CLS	0						
SSS	25	0,21	-1,54	-0,33			
SSL	0						
SLS	2	0,02	-4,07	-0,07			
SLL	3	0,03	-3,66	-0,09			

SPECIES	INDIVIDUALS
8	117

TABLE 40
Shannon Diversity calculated for the local map of SAL b Built-up 2017.

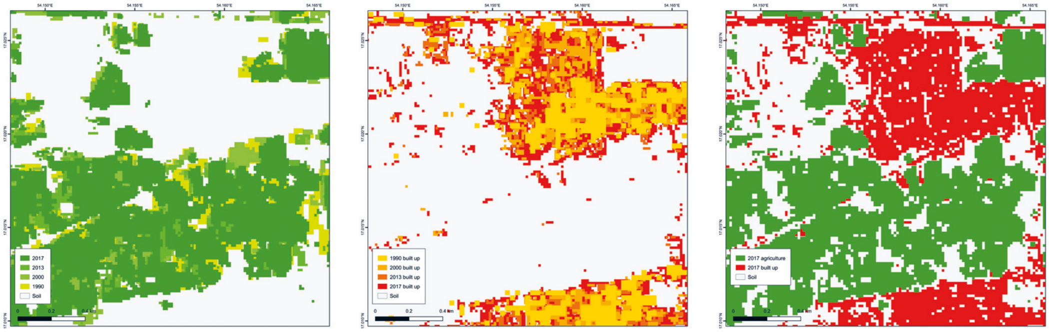


FIGURE 88
Local map of SAL c Agriculture/Built-up Area 2×2 km, 1:10.000, 1990–2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	38	0,72	-0,33	-0,24	**0,88**	2,08	**0,42**
CSL	0						
CLL	0						
CLS	0						
SSS	8	0,15	-1,89	-0,29			
SSL	0						
SLS	4	0,08	-2,58	-0,20			
SLL	3	0,06	-2,87	-0,16			

SPECIES	INDIVIDUALS
8	53

TABLE 41
Shannon Diversity calculated for the local map of SAL c Agriculture 2017.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	104	0,70	-0,35	-0,25	0,80	2,08	**0,39**
CSL	0						
CLL	0						
CLS	0						
SSS	35	0,24	-1,44	-0,34			
SSL	0						
SLS	4	0,03	-3,61	-0,10			
SLL	5	0,03	-3,39	-0,11			

SPECIES	INDIVIDUALS
8	148

TABLE 42
Shannon Diversity calculated for the local map of SAL c Built-up 2017.

SUMMARY OF FINDINGS

The mapping analysis and discussion of spatial diversity was conducted for four larger regions in Oman: the interconnected Muscat Capital Area; Al Batinah plain; the Omani interior around Nizwa; and the southern region of Salalah. Each region is subject to different urbanisation processes and land use change drivers. The cross-comparison allows drawing conclusions regarding the urbanisation processes and the future sustainable balance of land uses.

Muscat Capital Area shows various degrees of urban sprawl leading to the elimination of agricultural land uses in new residential neighbourhoods that form the predominant settlement pattern. The few remaining agriculture spots in former oasis settlements along the coast are under increasing stress. The same goes for the few natural vegetation areas such as the mangrove forest of Al Qurm. An urban design answer to this contingent but low density urbanisation can be found in urban infill, re-densification and sharing of spaces.

The Al Batinah region suffers significant agricultural land use loss, too. Here the process is directed in two ways: Infrastructure triggers urban development that encroaches on and erodes agricultural land use. This goes along with a fragmentation and isolation of remaining agriculture space. But urban expansion is also directed into the gravel desert provided this desert space can be served with water and connected to other urban areas by road networks. Urbanisation of Al Batinah increased in scale and speed, extending and surpassing that of Muscat Capital Area. An urban design answer to this urban sprawl is an adapted compact rural-urban settlement form.

In the region of Nizwa in the Omani interior the built-up space transgresses all parts of the agricultural land leading to a radical reconfiguration of the former oasis settlement systems. The result is a scattered and hollowed urban-agricultural carpet. Yet, this condition offers the highest spatial diversity and the best equilibrated Equitability between land uses. The spatial patterns of this region merit being replicated in other parts of Oman. An urban design answer to this rural-urban carpet is a delicate development and upgrading of both rural and urban spaces for mutual benefits and leveraging of rural-urban synergies.

Salalah exemplifies the conflict of land uses apparent in all parts of Oman in the most acute way. An urban design answer to this agricultural replacement is the integration of urban farming and the development of new forms of dense urban settlements. Based on these insights, this thesis develops the following alternative urbanisation models for Oman:

– Type Muscat: Urban Infill and Re-Densification
– Type Al Batinah: Compact Rural-Urban Settlements
– Type Nizwa: Upgraded Rural-Urban Mats
– Type Salalah: Urban Farming ●

P A R T

V

URBAN DESIGN STRATEGIES

PART 5: URBAN DESIGN STRATEGIES

This chapter applies spatial diversity as a criterion for sustainable urban design. Status quo maps and their spatial diversity indices (see chapter 4) are compared to alternative scenario maps and their respective spatial diversity indices. These alternative scenarios are based on urban design strategies that address, and work within, the existing situation rather than proposing new towns without local context. The urban design strategies are rooted in the critique of the status quo and new urban design principles developed for Oman (see chapter 3). The main urban design principles are mixed-use residential and agriculture, low-rise high-density, and compactness and re-densification. The focus is on land use and not infrastructure development. The improved indices are closer to the maximum index value of Hmax = 2.08. The alternative scenarios thereby become valid development strategies for representative urban conditions in Oman. Each examined region follows a set of specific steps:

- Status Quo. The spatial diversity distribution and score of the status quo identify potential locations for, and additions of, underrepresented space species in the new alternative scenario.
- Urban Design Strategy. The urban design strategy addresses the context of the urban design intervention and prioritises the spatial allocation and addition of space species accordingly. The process is translated into an alternative scenario land use map.
- Improved Spatial Diversity Index. The alternative scenario land use map is evaluated with the spatial diversity index. The urban design strategies leading to the alternative scenario are thus validated by an improved spatial diversity index score.
- Model and Visualisation. Status quo and alternative scenario maps drive the CityEngine models and visualise possible urban forms as interactive 3D models that can be explored visually and quantitatively.

TYPE MUSCAT: URBAN INFILL

The selected location MCA 1a in Muscat Capital Area is a newly planned residential neighbourhood. It was planned for ca. 2000 plots of mainly individual villas. This ‘monoculture’ of residential plots of similar size results in a low spatial diversity index (H = 1.11). The imbalance of residential to (non-existent) agricultural spaces needs to be addressed, too. Presently, only ca. 70% of the plots are developed. This opens up possibilities for an alternative urban development on the remaining 30% to balance the agricultural-residential ratio and the low spatial diversity. The urban design strategy thus identifies underrepresented spatial species and allocates them on vacant spaces. The agricultural typology grafts onto vacant spaces currently reserved for future roads and residual spaces. The residential typology builds on vacant residential lots. It introduces a new housing typology of contact courtyard houses with gardens offering the same usable floor area as conventional villas on half the plot size.

Status Quo.
The status quo score highlights the species gaps in the region examined. Five out of eight species are currently underrepresented. Since the status quo offers an additional 30% vacant spaces, the target individual count can be increased by 30% from 333 to ca. 440 and an ideal average distribution of each species of 55 (SEE TABLE 43).

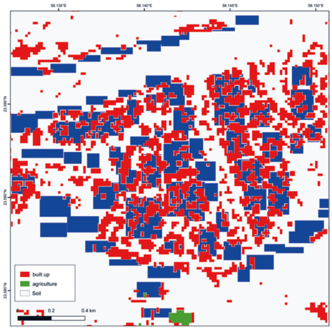
The status quo maps show the potential locations for underrepresented space species. These additional vacant spaces are located on reserved areas for roads and residential plots. They comprise about 30% of the spaces. The urban design strategy aims for a compact settlement pattern and does not aim to use land outside of the settlement core (gravel desert in grey). It further keeps the existing transport infrastructure (SEE FIGURE 89).

Urban Design Strategy. The urban design strategy allocates space species onto the potential maps. The new resulting alternative scenario map shows higher spatial density and diversity while to a certain extent repairing the status quo (SEE FIGURE 90).

Improved Spatial Diversity Index. The alternative scenario shows an improved score. The representation of species is more equal, with most species near the average. The total number of species increases to 461. Diversity across the species is higher, with a new H=1.76 as compared to H=1.11 (SEE TABLE 44).

Model and Visualisation. The status quo and alternative scenario map can now be used to generate comparative 3D visualisation. The status quo adequately represents the current situation of residential 'monoculture' and vacant spaces (SEE FIGURES 91–94).

The alternative scenario shows how dedicated agricultural spaces and new residential typologies increase the spatial density and diversity.



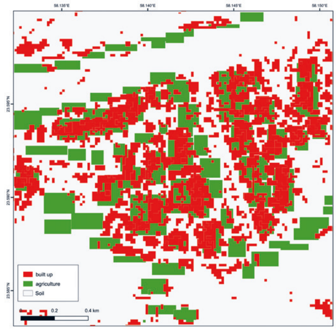


FIGURE 89
Potential maps – locations for underrepresented space species (mapped in blue) in the status quo map of MCA 1a 2017 2×2 km 1:10.000.

FIGURE 90
Alternative scenario map of MCA 1a 2×2 km 1:10.000.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	179	0,54	-0,62	-0,33	**1,11**	2,08	**0,53**
CSL	**0**						
CLL	**0**						
CLS	**1**	0,00	-5,81	-0,02			
SSS	43	0,13	-2,05	-0,26			
SSL	**1**	0,00	-5,81	-0,02			
SLS	**12**	0,04	-3,32	-0,12			
SLL	97	0,29	-1,23	-0,36			

SPECIES	INDIVIDUALS	AVERAGE
8	333	41,63

TABLE 43
Shannon Diversity calculated for the status quo map of MCA 1a 2017 with gaps highlighted (in bold).

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	179	0,39	-0,95	-0,37	**1,76**	2,08	**0,85**
CSL	**23**	0,05	-3,00	-0,15			
CLL	**31**	0,07	-2,70	-0,18			
CLS	**28**	0,06	-2,80	-0,17			
SSS	43	0,09	-2,37	-0,22			
SSL	**18**	0,04	-3,24	-0,13			
SLS	**42**	0,09	-2,40	-0,22			
SLL	97	0,21	-1,56	-0,33			

SPECIES	INDIVIDUALS	AVERAGE
8	461	57,63

TABLE 44
Shannon Diversity calculated for the alternative scenario map of MCA 1a.

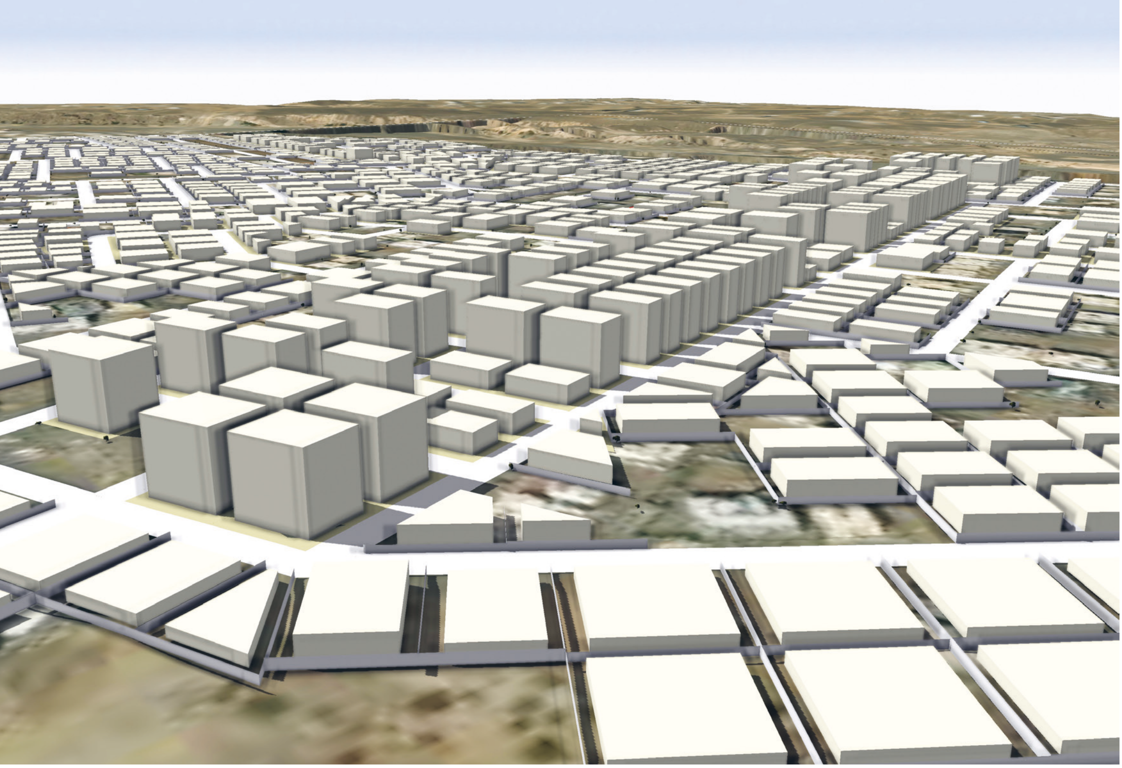


FIGURE 91
Visualisation of status quo for MCA 1a 2017.

FIGURE 92
Plan of status quo for MCA 1a 2017.

FIGURE 93
Visualisation of alternative scenario for MCA 1a.

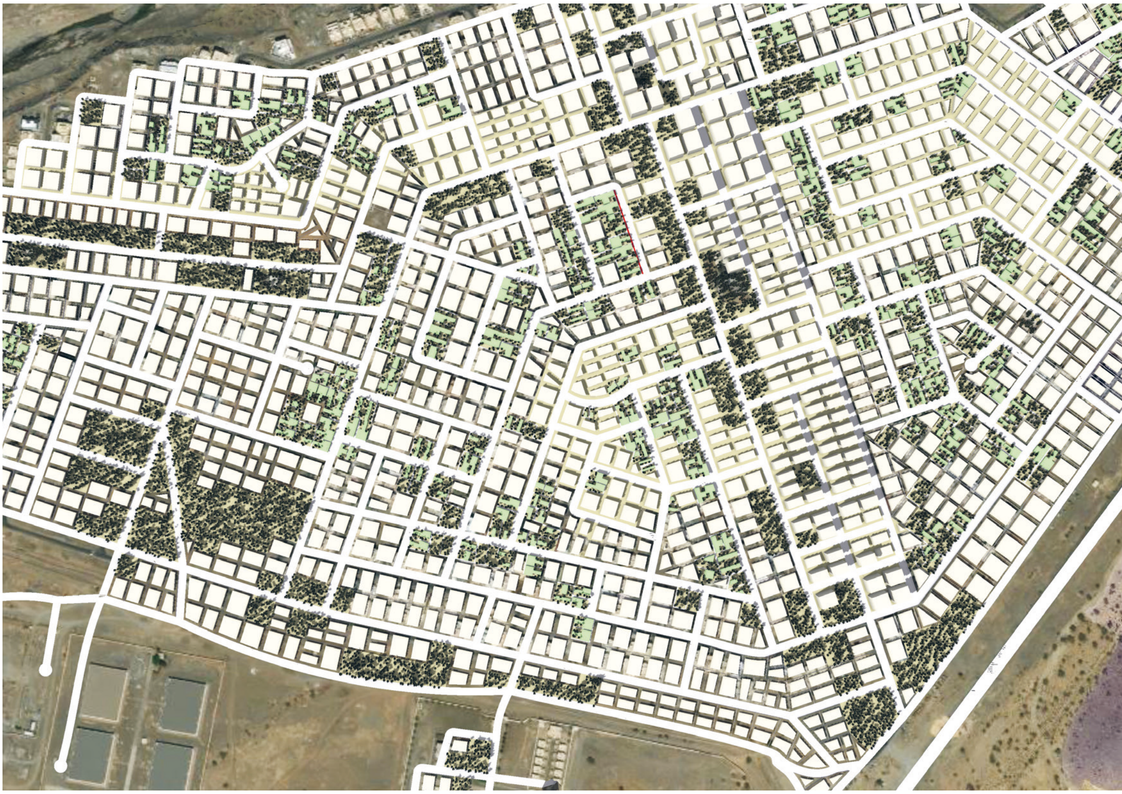


FIGURE 94
Plan of alternative scenario for MCA 1a.

TYPE AL BATINAH: COMPACT RURAL-URBAN SETTLEMENTS

The selected location MCA 2a in the Al Batinah region outside of Muscat Capital Area is located in the rural-urban interface. The coastal oasis agriculture has deteriorated and is now highly fragmented. The relative proximity to Muscat Capital Area and the coastal highway towards the United Arab Emirates in the North form a major urbanisation vector. The urban design strategy aims to revitalise coastal oasis settlements by creating new agricultural nuclei and activate fallow spaces. This will reconnect former isolated settlements, relieve pressure from adjacent desert spaces and counteract urban fragmentation and sprawl. The result is a compact rural-urban settlement form applicable to all the coastal areas of Oman.

Status Quo.
The status quo score highlights the species gaps in the region examined. Four out of eight species are currently underrepresented. Since the status quo offers additional 50% fallow land in form of deteriorated oases and vacant spaces. Therefore, the target individual species count can be increased by 50% from 372 to ca. 700 and an ideal average distribution of each species of 55 (SEE TABLE 45).

The status quo maps show the potential locations for underrepresented space species. These additional vacant spaces are located on reserved areas for roads and residential plots. They comprise about 30% or the spaces. The urban design strategy aims for a compact settlement pattern and does not aim to use land outside of the settlement core (gravel desert in grey). It further keeps the existing transport infrastructure (SEE FIGURE 95).

Urban Design Strategy. The urban design strategy allocates space species onto the potential maps. The focus is laid on the creation of new agricultural nuclei that revitalise the former coastal oasis structure while achieving higher spatial density and diversity (SEE FIGURE 96).

Improved Spatial Diversity Index. The alternative scenario shows an improved score. The representation of species is more equal with most species near the average of 79.6. The total number of species increase to 637. Diversity across the species is higher with a new H=1.87 as compared to H=1.10 (SEE TABLE 46).

Model and Visualisation. The status quo adequately represents the current situation of deteriorated coastal oasis settlements and fallow spaces. The alternative scenario shows how oasis nuclei revitalise compact coastal village settlements while increasing the spatial density and diversity (SEE FIGURES 97–100).

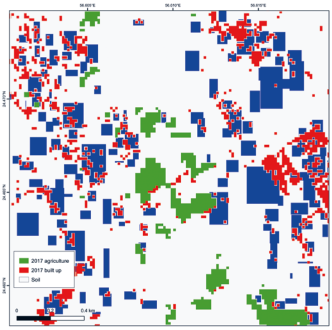
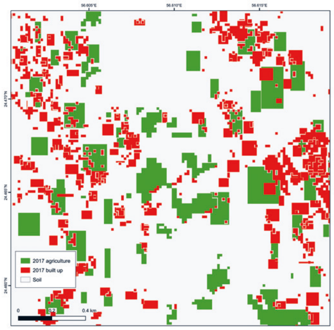
 

FIGURE 95
Potential maps – locations for underrepresented space species (mapped in blue) in the status quo map of MCA 2a 2017 2×2 km 1:10.000.

FIGURE 96
Alternative scenario map of MCA 2a 2×2 km 1:10.000.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	224	0,60	-0,51	-0,31	**1,10**	2,08	**0,53**
CSL	**0**						
CLL	**0**						
CLS	**3**	0,01	-4,82	-0,04			
SSS	33	0,09	-2,42	-0,21			
SSL	**0**						
SLS	33	0,09	-2,42	-0,21			
SLL	79	0,21	-1,55	-0,33			

SPECIES	INDIVIDUALS	AVERAGE
8	372	46,50

TABLE 45
Shannon Diversity calculated for the status quo map of MCA 2a 2017 with gaps highlighted (in bold).

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	224	0,35	-1,05	-0,37	**1,87**	2,08	**0,90**
CSL	**89**	0,14	-1,97	-0,27			
CLL	**54**	0,08	-2,47	-0,21			
CLS	**68**	0,11	-2,24	-0,24			
SSS	33	0,05	-2,96	-0,15			
SSL	**57**	0,09	-2,41	-0,22			
SLS	33	0,05	-2,96	-0,15			
SLL	79	0,12	-2,09	-0,26			

SPECIES	INDIVIDUALS	AVERAGE
8	637	79,63

TABLE 46
Shannon Diversity calculated for the alternative scenario map of MCA 2a.

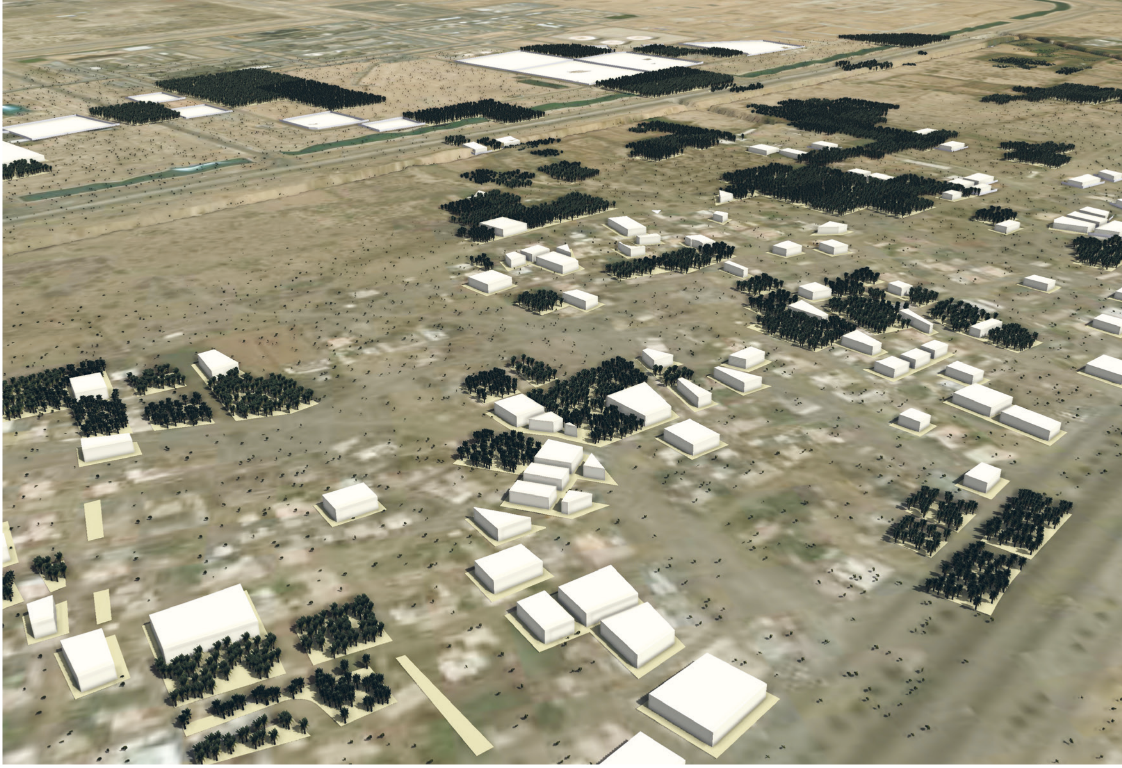


FIGURE 97
Visualisation of status quo for MCA 2a 2017.

FIGURE 98
Plan of status quo for MCA 2a 2017.

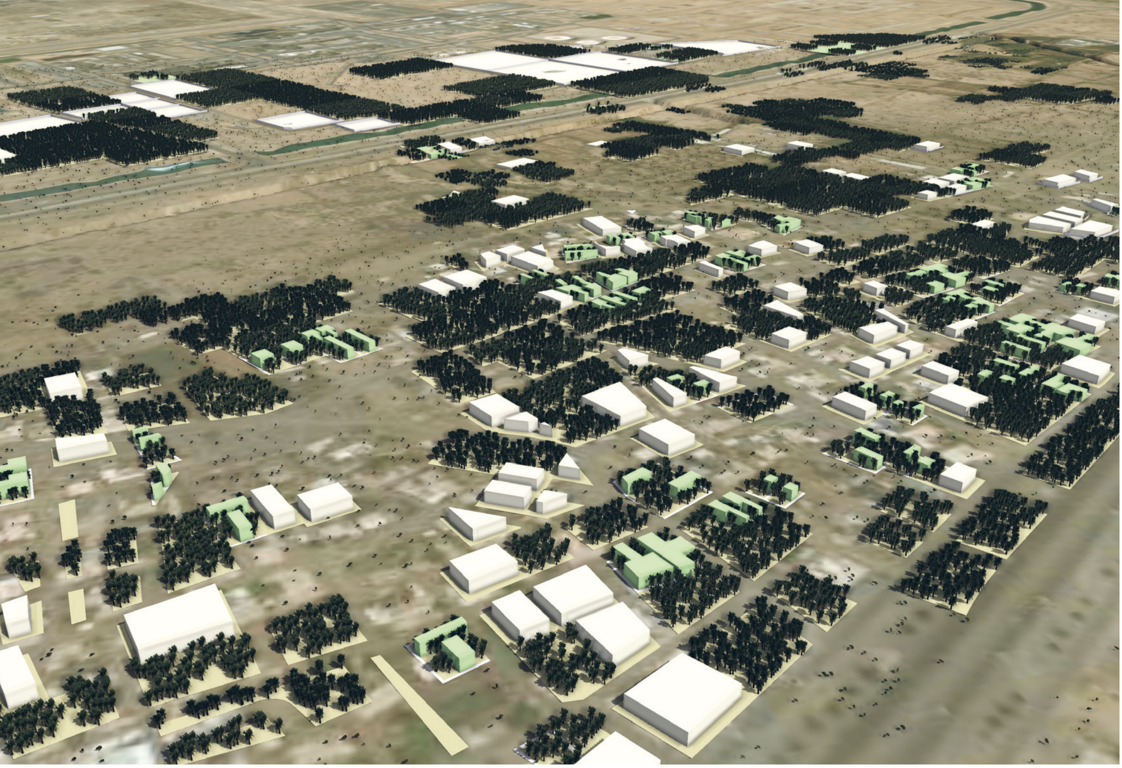


FIGURE 99
Visualisation of alternative scenario for MCA 2a.

FIGURE 100
Plan of alternative scenario for MCA 2a.

TYPE NIZWA: UPGRADED RURAL-URBAN MATS

The selected location NIZ b in the interior region of Oman offers a second rural-urban interface paradigm. The oasis settlements of the interior differ from the coastal ones as they are fed by upstream sources rather than underground water. This accounts for a traditionally linear, fan-like settlement structure. The current state of the interior oases is also fragmented and isolated resulting in a scattered urban-agricultural carpet. The current balance of agricultural and residential spaces is good, yet spatially inefficient, sprawling and not very diverse. The urban design strategy also frames the oases with an urban edge.

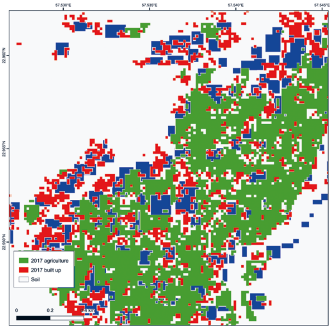
Status Quo.
The status quo score highlights the species gaps in the region examined. Five out of eight species are currently underrepresented. Since the status quo offers an additional 40% vacant spaces the target individual count can increase by 40% from 502 to ca. 700 and an ideal average distribution of each species of 86 (SEE TABLE 47).

The status quo map shows the potential locations for underrepresented space species. These spaces are mainly located on deteriorated areas inside the oasis settlement and in between new residential settlement areas outside of it. They comprise about 40% of the available the spaces (SEE FIGURE 101).

Urban Design Strategy. The urban design strategy allocates space species onto the potential maps, aims for a reconnected oasis settlement and frames the oasis edges with urban settlements (SEE FIGURE 102).

Improved Spatial Diversity Index. The alternative scenario shows an improved score. The representation of species is more equal, with most species closer to the average. The total number of species increases to 690. Diversity across the species is higher with a new H=1.72 as compared to H=1.02 (SEE TABLE 48).

Model and Visualisation. The status quo adequately represents the current situation of an oasis settlement under stress from urban sprawl. The alternative scenario shows how repairing and framing the oasis settlement create a more connected urban-agricultural tissue with clear edge condition, legibility and increasing spatial density and diversity (SEE FIGURES 103–106).



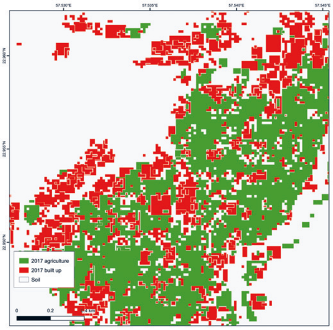


FIGURE 101

Potential maps – locations for underrepresented space species (mapped in blue) in the status quo map of NIZ b 2017 2×2 km 1:10.000.

FIGURE 102

Alternative scenario map of NIZ b 2×2 km 1:10.000.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	308	0,61	-0,49	-0,30	**1,02**	2,08	**0,49**
CSL	**0**						
CLL	**0**						
CLS	**0**						
SSS	67	0,13	-2,01	-0,27			
SSL	**0**						
SLS	**17**	0,03	-3,39	-0,11			
SLL	110	0,22	-1,52	-0,33			

SPECIES	INDIVIDUALS	AVERAGE
8	502	62,75

TABLE 47

Shannon Diversity calculated for the status quo map of NIZ b 2017 with gaps highlighted (in bold).

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	308	0,45	-0,81	-0,36	**1,72**	2,08	**0,83**
CSL	**42**	0,06	-2,80	-0,17			
CLL	**37**	0,05	-2,93	-0,16			
CLS	**41**	0,06	-2,82	-0,17			
SSS	67	0,10	-2,33	-0,23			
SSL	**39**	0,06	-2,87	-0,16			
SLS	**46**	0,07	-2,71	-0,18			
SLL	110	0,16	-1,84	-0,29			

SPECIES	INDIVIDUALS	AVERAGE
8	690	86,25

TABLE 48

Shannon Diversity calculated for the alternative scenario map of NIZ b.

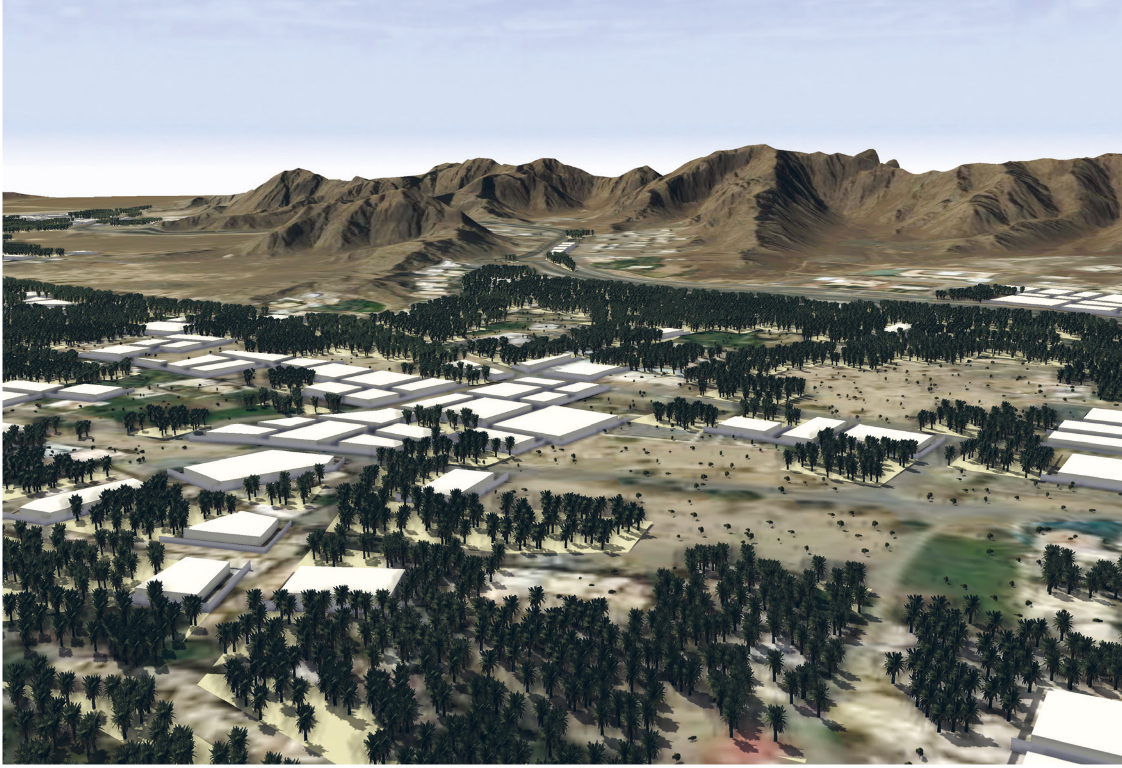


FIGURE 103
Visualisation of status quo for NIZ b 2017.

FIGURE 104
Plan of status quo for NIZ b 2017.

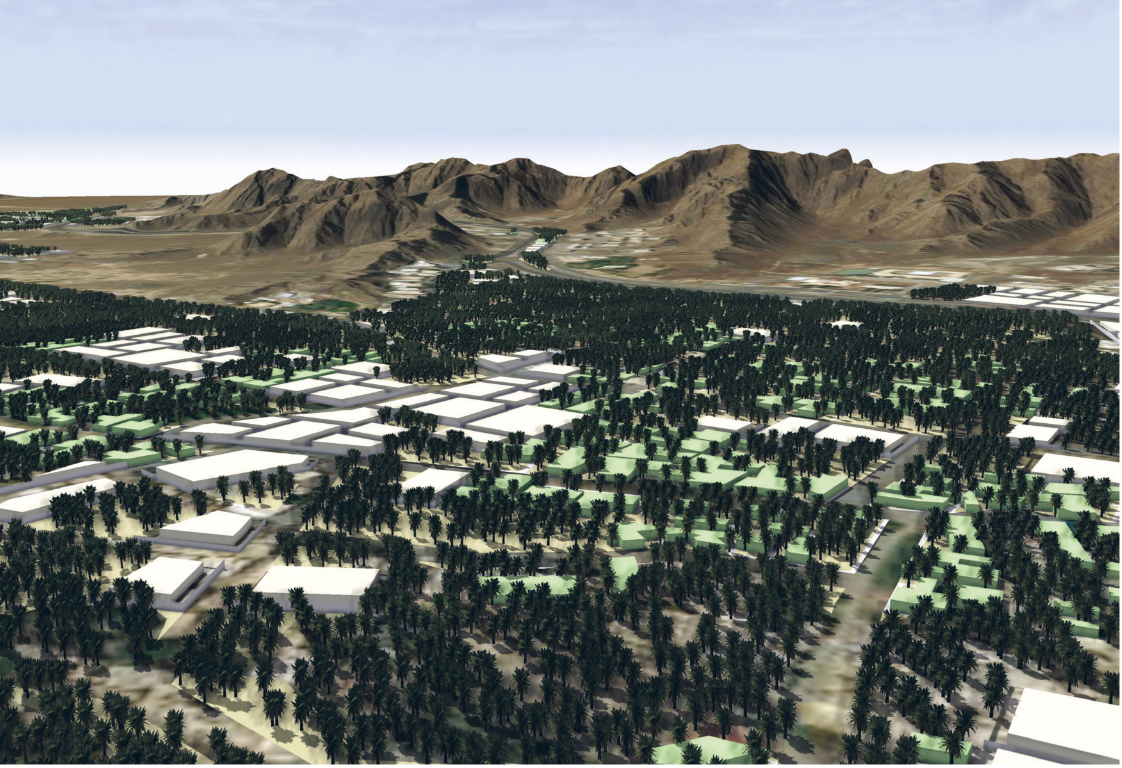


FIGURE 105
Visualisation of alternative scenario for NIZ b.

FIGURE 106
Plan of alternative scenario for NIZ b.

TYPE SALALAH: URBAN FARMING

The selected location SAL c in Salalah, in the southern region of Oman, is the location selected for the last case study for the application of spatial density as a measure of urban design. Due to the seasonal monsoon rain, Salalah offers plenty of ground water to irrigate tropical gardens. However, these gardens are threatened by unplanned urban encroachment on the one side, and by neglect of agriculture on the other. The urban design strategy envisages the integration of urban farming and the development of new forms of dense urban settlements.

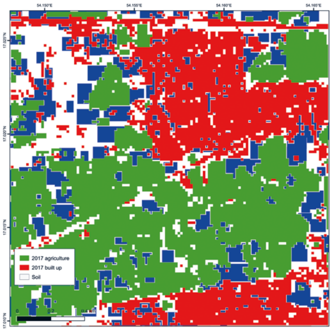
Status Quo.
The status quo score highlights the species gaps in the region examined. Six out of eight species are currently underrepresented. Since the status quo offers an additional 20% vacant spaces, the target individual count can be increased by 20% from 201 to ca. 250 and an ideal average distribution of each species of 34.5 (SEE TABLE 49).

The status quo map shows the potential locations for underrepresented space species. These additional vacant spaces are located on reserved areas for roads and residential plots. They comprise about 30% of the spaces. The urban design strategy aims for a compact settlement pattern and does not use land outside of the settlement core (gravel desert in grey). It further keeps the existing transport infrastructure intact (SEE FIGURE 107).

Urban Design Strategy. The urban design strategy allocates space species onto the potential maps. The new resulting alternative scenario map shows higher spatial density and diversity while to a certain extent repairing the status quo (SEE FIGURE 108).

Improved Spatial Diversity Index. The alternative scenario shows an improved score. The representation of species is more equal, with most species near the average. The total number of species is increased to 277. Diversity across the species is higher, with a new H=1.59 as compared to H=0.82. The lower result is due to the fact that the space for additional development is restricted and the status quo has a relatively biased starting distribution (SEE TABLE 50).

Model and Visualisation. The status quo adequately represents the current situation of dilapidated urban gardens and sub-urbanisation. The alternative scenario shows how reconnected urban gardens and a network of urban nuclei increase the spatial density and diversity (SEE FIGURES 109–112).



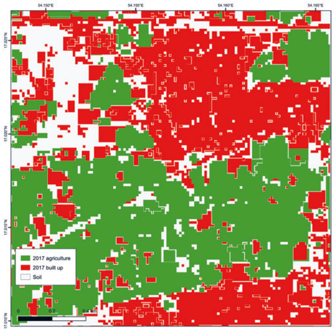


FIGURE 107

Potential maps – locations for underrepresented space species (mapped in blue) in the status quo map of SAL c 2017 2×2 km 1:10.000.

FIGURE 108

Alternative scenario map of SAL c 2×2 km 1:10.000.

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	142	0,71	-0,35	-0,25	**0,83**	2,08	**0,40**
CSL	**0**						
CLL	**0**						
CLS	**0**						
SSS	43	0,21	-1,54	-0,33			
SSL	**0**						
SLS	**8**	0,04	-3,22	-0,13			
SLL	**8**	0,04	-3,22	-0,13			

SPECIES	INDIVIDUALS	AVERAGE
8	201	25,13

TABLE 49

Shannon Diversity calculated for the status quo map of SAL c 2017 with gaps highlighted (in bold).

SPECIES	NUMBER	PI	LNPI	PI*LNPI	H	HMAX	EQUITABILITY
CSS	142	0,51	-0,67	-0,34	**1,59**	2,08	**0,76**
CSL	**18**	0,06	-2,73	-0,18			
CLL	**17**	0,06	-2,79	-0,17			
CLS	**11**	0,04	-3,23	-0,13			
SSS	43	0,16	-1,86	-0,29			
SSL	**18**	0,06	-2,73	-0,18			
SLS	**12**	0,04	-3,14	-0,14			
SLL	**16**	0,06	-2,85	-0,16			

SPECIES	INDIVIDUALS	AVERAGE
8	277	34,63

TABLE 50

Shannon Diversity calculated for the alternative scenario map of SAL c.

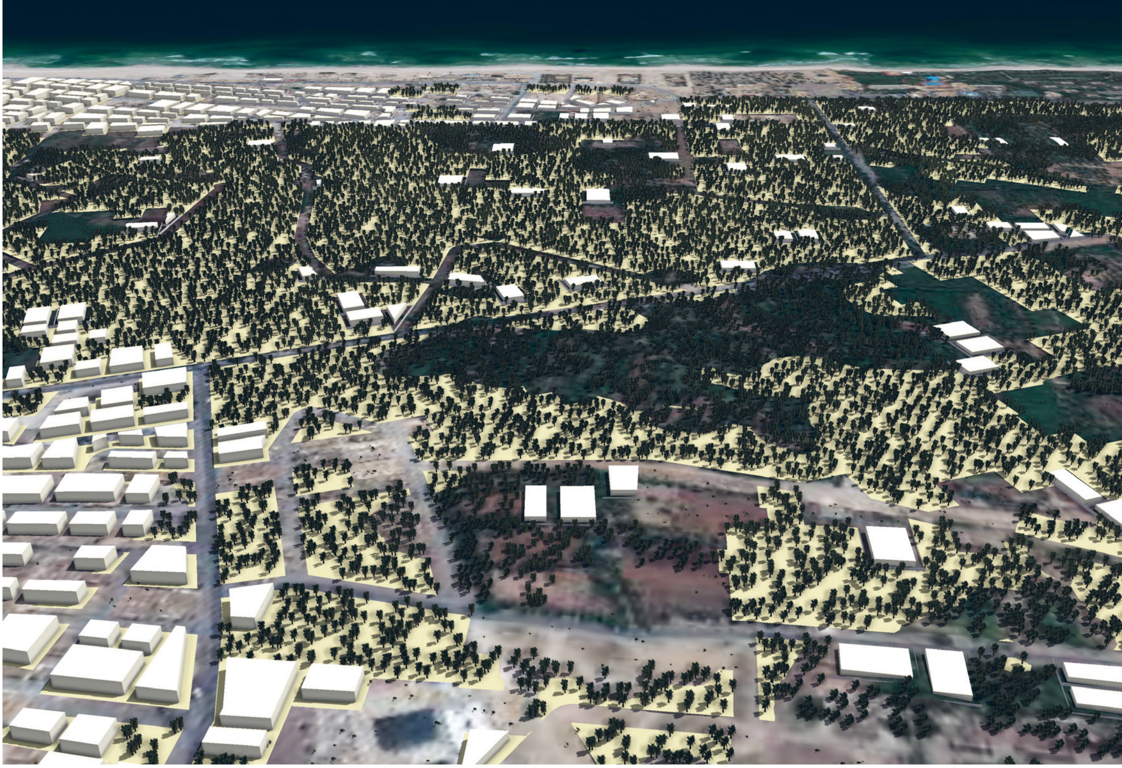


FIGURE 109
Visualisation of status quo for SAL c 2017.

FIGURE 110
Plan of status quo for SAL c 2017.

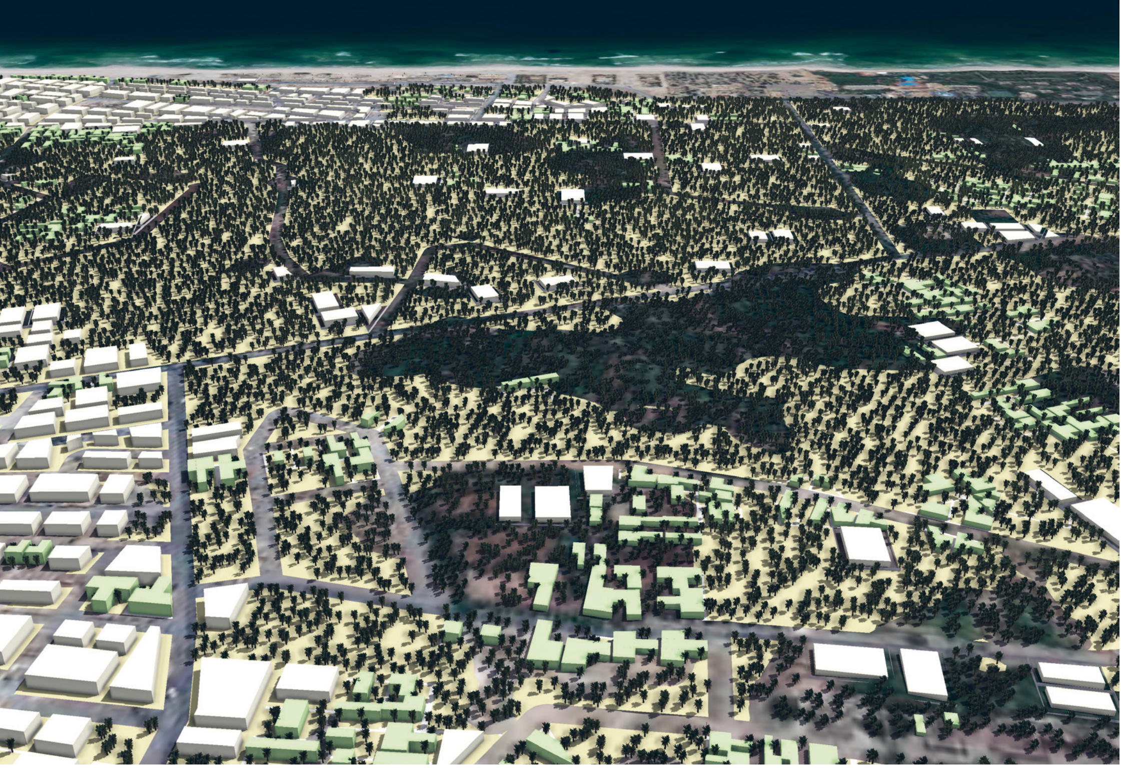


FIGURE 111
Visualisation of alternative scenario for SAL c.

FIGURE 112
Plan of alternative scenario for SAL c.

TYPOLOGICAL COMPARISON

The four cases examine typical urban conditions of the land use transformation in Oman. They offer different potentials of development based on the available vacant, fallow or edge land, ranging from 20–50% development space. Each case is specific to its context but was chosen for its relevance to Oman. Most urban and rural regions of Oman can be directly compared to one of the cases in terms of urban structure, morphology, function and land use. The urban design strategies address the spatial development potential, distribution of space species and the local context. The urban design strategies presented here form a catalogue of contextual urban design responses that can be expanded and transferred to other comparable urban situations in Oman and elsewhere. The results are visualised in interactive 3D models. These visualisations are not meant to prescribe urban development pathways, but rather to help illustrate alternatives and link the abstract representation of spatial diversity maps to urban form. The visualisations show that the improved spatial diversity can drive balanced, liveable, sustainable and resilient agricultural residential settlement patterns. ●

PART VI

DISCUSSION

PART 6: DISCUSSION

This dissertation proposes a conceptualisation of spatial diversity based on four theoretical topoi:

> First, Lefebvre's theory of the production of space, which underscores the fact that space is a social construct. Social production and malleability of space open up the possibility to describe land use transformation. Space in itself is the resource and the result of this socially constructed process. In the context of Oman, this implies a differentiated look at spaces of agriculture, residence and the desert.
>
> Second, the concept of extended urbanisation, which dismantles the artificial separation and conceptualisation of urban and non-urban spaces. Since all spaces are now subject to urbanisation the precise degrees in which these transformation processes take place are relevant. This opens up the possibility for further differentiation between urbanising spaces and 'real/radical outsides' that cannot be urbanised. This thesis adds a regional perspective to this discourse that so far has rarely tackled the particularities of desert territories, in particular Oman.
>
> Third, the concept of urban metabolism, which allows linking stocks and flows of people, energy, material and water to system boundaries or observation scales. The quantification of these stocks and flows across spaces reveals that agricultural spaces are the most valuable and indispensable. Their extent is directly linked to the scarce resource of fresh water. Agricultural spaces dynamically support residential spaces. Together, they form the urbanising regions of Oman. Due to the scarcity of fresh water a sustainable urbanisation in Oman cannot cover more than 3-5% of the territory (as the sum of built up and agricultural space; see chapter 3: Methods and Data - Map Analysis).
>
> Fourth, the concept of urban sustainability, which has just begun to include spatial dimensions next to social, economic and ecological ones. This thesis offers a new metric to describe spaces, namely their degree of spatial diversity. This requires understanding spaces as abstract and transformable constructs (see Lefebvre), including all spaces of urban

transformation (see extended urbanisation) and qualifyimg these spaces based on their urban metabolic rates (see urban metabolism). This allows conceptualising space species and facilitates application of the concept of spatial diversity.

The dissertation also reviews historic urbanisation constraints, examines pre-modern land use structures, traces Oman's path to modernity and comments on its changing rural systems and legacy of planning strategies. This complex Omani urbanisation context has not been examined previously, nor has the Omani case been discussed systematically within the larger discourse on space, urbanisation and sustainability in this way before.

This dissertation develops a method to map land use transformation across Oman at different times and in different scales with remote-sensing of satellite images. It then applies Shannon's diversity concept to statistical analysis of spatial diversity. This differentiated spatial, temporal and structural understanding of land use transformation in Oman reveals gradients of urban transformation. Knowledge of spatial diversity will lead to a more resilient and sustainable urbanisation in Oman. This is demonstrated in urban design strategies for four cases.

ANSWERING THE RESEARCH QUESTIONS

Based on this theoretical foundation, the methodological approach and the findings presented, the research questions (RQ) of this dissertation can now be answered as follows:

– *RQ 1: How can we discern, map and measure spatial diversity at various scales in Oman considering the complex and multidimensional processes that unfolded since 1970?*
  This question is answered in chapter 3 – Methods and Data – by a literature review of urbanisation in Oman, remote-sensing to map land use transformation across Oman, and analysis in terms of spatial diversity in chapter 4 – Findings – revealing different degrees of spatial diversity across Oman.

– *RQ 2: How do we need to adapt current concepts of sustainable urbanisation to include spatial diversity?*
  This question is answered in chapter 1 – Hypothesis and State of Research – by expanding on the four theoretical topoi:

production of space, extended urbanisation, urban metabolism and development of spatial diversity. The urgency to adapt current concepts of sustainability is emphasised in chapter 2 – Threatened Spatial Diversity in Oman – by a review and critique of specific urbanisation constraints, historic development legacies and fragile rural systems.

– *RQ 3: How can we develop alternative urban design strategies based on the new approach to urban sustainability focussing on the key interlinked aspects of housing and agriculture?*
  This question is answered in chapter 5 – Urban Design Strategies – where four such design strategies are developed taking spatial diversity into account. These strategies use procedural modelling to visualise alternative urban design scenarios as interactive 3D models.

LIMITATIONS TO THE RESEARCH

The metric of spatial diversity derives from statistical analysis of remote-sensed maps. This method has inherent imitations and constraints that affect the significance and validity of the following interpretation and conclusion towards urbanisation strategies in Oman. To overcome these current limitations will require broader research on spatial diversity in the future:

INPUT DATA DETERMINATION

A first limitation derives from the input data available for this research. The dataset (Landsat) was chosen as the best available, given the scale and time-frame of observation and desirable, yet manageable resolution for the spatial diversity analysis. While developing the method a choice had to be made between increased complexity of space species, observation range and error margins. As mentioned above, the exercise was conducted with remote-sensed satellite images with a resolution of 15×15 m, for one time stamp (2017) and was reduced to two sets of land uses: agricultural and built-up spaces. The method was calibrated and ground-truthed to assure the best possible extraction of information based on the available data. In return, this means that different spatial-input data in terms of scale, resolution, or temporal parameters can yield different spatial diversity ranges.

DUAL LAND USE CONCEPT

A second limitation is due to the opposing setup of competing and conflicting land uses in Oman: the simplified duality of agricultural and built-up spaces. The concept of spatial diversity also merits exploration beyond the dual setup and in synergetic rather than oppositional settings. This would require a different approach to remote-sensing and a further theoretical understanding of urban design and planning challenges. In principle, all types of land cover such as wetlands, water bodies, mountains, different kinds of deserts, industrial and military areas could be included. Important urban transformation components such as transport, energy and water infrastructure, for instance, follow a network development that cannot easily be mapped onto spatial diversity. Further research needs to be done to explore the interlinkages of networks and spaces.

CONTEXT DEPENDENCY

A third limitation is the context dependency of spatial diversity. Spatial diversity remains, just like bio-diversity, a relative indicator. Even though it measures spaces that can ultimately be summed up in terms of their square metre size, it should never be taken for absolute value. This also means that the initial definition of space species depends on both the research question and the available data. In other words, spatial diversity is not an automatism, but needs to be rooted in contextual spatial research to be meaningful. At best, spatial diversity can support urban design strategies and promote accessible, transparent and participatory planning. In the worst case, an undifferentiated application of spatial diversity leads to the 'conservation' of inflexible spatial areas. The aim of this thesis was to demonstrate that spatial diversity can inform urban design, yet a higher spatial diversity does not automatically result in increased sustainability.

COMPLEXITY OF URBAN SUSTAINABILITY

A fourth limitation is that the overall definition of urban sustainability has not become easier by introducing this metric. Rather, it has been expanded to include measurable spatial diversity. As the spatial diversity index is dependent on context, data and interpretation, this adds further layers of complexity.

TRANSFERABILITY TO OTHER CONTEXTS

The concept of spatial diversity was applied to a specific, complex and large territory that requires elaborate contextualisation. Oman was chosen not just because of its relatively young land transformation and urbanisation history, dating back only to 1970, or the stark contrast of limited agricultural resources to strong urbanisation pressure, making it a suitable and relatively under-researched candidate. Conflicting land uses like those in Oman, scarce spatial resources, the degradation of landscape, the impact of climate change on arid regions, etc. are indeed phenomena also found elsewhere. The observations made in Oman can thus be transposed to other settings, if only in parts, and add to the significance of the research. Similar geographic, historic, demographic, socio-political and economic conditions can be found across the Arabian Peninsula and beyond. The problems of unbalanced land use are even more acute in city states like Dubai or Kuwait and in smaller territorial entities like Qatar and Bahrain. [331] The rapid urbanisation of coastal areas and economic centres is also a key feature of Saudi Arabian urbanisation. All these urban settings will need to manage their spatial resources with the limited renewables in the very near future. [332]

Arid and semi-arid regions around the world are expanding dramatically (SEE FIGURE 113). [333] Desertification is linked to unilateral land use. [334] Spatial diversity and the focus on balanced agricultural and residential development are key strategies for resilient development in the future.

331 Wippel et al., *Under Construction*.
332 UN HABITAT, "The State of the Arabian Gulf Council Cities (Sultanate of Oman)."
333 Brinkmann et al., "Use of Environmental Predictors for Vegetation Mapping in Semi-Arid Mountain Rangelands and the Determination of Conservation Hotspots."
334 GreenFacts, "Desertification."

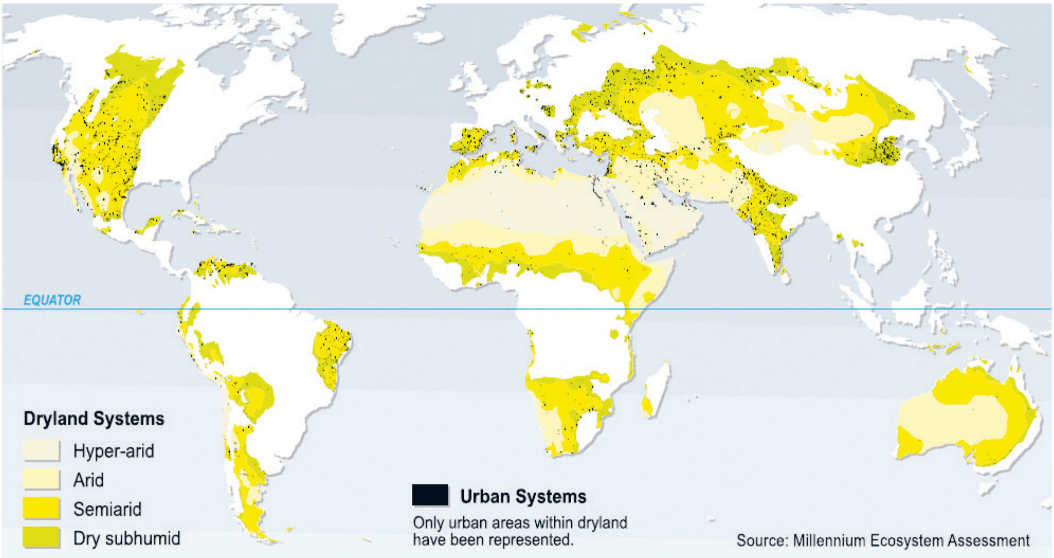


FIGURE 113
Global arid and semi-arid regions based on Millennium Ecosystem Assessment, 2005.

The concept of spatial diversity can be applied to any global spatial transformation process. Among the most pressing challenges in the global South are the rural-urban interfaces where urbanisation threatens traditional agriculture and undermines food production. In monsoon Asia the concept of rural-urban transition has been described as 'desakota' [Indonesian for 'village-city']. 335 Enriching desakota research with spatial diversity indices could be very significant to better understand and manage these crucial land uses in the future.

OUTLOOK AND FURTHER RESEARCH

The space species presented here refer to only two land use categories – agricultural and urban spaces – that have been identified through literature review and fieldwork as the most important in the context of Oman. However, the concept of space species and spatial diversity is scalable, transferable and overlaps with current research in other fields. It could be expanded to many more space species, to different observation scales and regions.

335 Desakota Study Team (DST), "Re-Imagining the Rural-Urban Continuum: Understanding the Role Ecosystem Services Play in the Livelihoods of the Poor in Desakota Regions Undergoing Rapid Change."

The demonstrated method of remote-sensing and statistical analysis could be automated and performed at regular intervals to monitor changes in spatial diversity. Further land uses could be analysed together to identify potential land use conflicts, in the same way as the juxtaposition of agricultural and urban land use in this dissertation, or by studying synergetic land uses that merit support and protection. Similar to recent regional and global land cover change surveys spatial diversity could be mapped at various places, times and scales across the globe. [336] The measurement of spatial diversity indices could be integrated as analytic tools into parametric urban design software such as CityEngine or Grasshopper. [337]

As with bio-diversity discourse that expanded only since the 1980s and now influences a multiplicity of research fields, methods and applications, many further areas of exploration are possible for spatial diversity as well. This is particularly interesting as remote-sensing becomes more affordable and precise, and urban modelling knowledge and computational power increase. Similar challenges existed in the bio-diversity discourse where advances in knowledge and technology allowed expanding scientific frontiers to chart unfamiliar territories. Urban design exploration theory has also developed other links, for instance to biology, with the recent advent of genetic algorithms. These concepts could be applied to space species to describe inherent 'spatial DNA' in the form of informative parameters for better adapted land use transformation and urban design. This is comparable to the research on accessibility and diversity within urban patterns such as done by Space Syntax. [338]

Despite its limitations, the concept of spatial diversity is highly significant in the context of sustainable urbanisation in Oman and beyond. In the light of climate change and ongoing desertification of large parts of the planet, this thesis has near-global relevance. Spatial diversity can be applied to any spatial category and therefore transferred to other geographic contexts. Since it is based on automated processes spatial diversity can, in the future, also be implemented with artificial intelligence. Possible applications could support new forms of evidence-based urban science and sustainable urbanisation. ●

336 Hansen et al., "High-Resolution Global Maps of 21st-Century Forest Cover Change."
337 "DeCodingSpaces Toolbox."
338 "Space Syntax"; Hillier, *Space Is the Machine*, 288.

PART VII

APPENDIX

PART 7: APPENDIX
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Zünd, Daniel. “A Meso-Scale Framework to Support Urban Planning.” Dissertation, ETH Zürich, 2016. https://doi.org/10.3929/ethz-a-010800421.

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2004–2005	Junior Architect, Stuerm Wolf, Zurich, Switzerland
2000–2001	Internship, von Gerkan, Marg & Partner, Hamburg, Germany

Professional Affiliations

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2007–2009	Visiting Assistant Professor, Knowlton School of Architecture, The Ohio State University, U.S.A.

Awards and Honors

- Deans Award. 2005 Princeton, New Jersey: Princeton University, U.S.A.
- Scholarship IKEA Foundation Switzerland, 2005–07. Switzerland.
- Travel-Research Scholarship Erich Degen Foundation – 2004 Department of Architecture, ETH Zurich, Switzerland.

Administrative Experience

- Coordinator: Learning Event on Disruptive Technologies for Development for the World Bank. Singapore ETH Centre, 2018.
- Coordinator: Postgraduate Summer School Engineering for Development (E4D) with ETH Global and TU Delft, 2016.
- Conference Workshop Panel: Arab Gulf Cities in Transition: Space, Politics and Society. With A., Deffner, V., & Babar, Z. Gulf Research Centre, 2016.
- Young Researcher Symposium Organisation. With Papadopoulou, M. Future Cities Laboratory, Singapore 2016.
- Conference and Exhibition organisation: Challenges of Urbanization in Arab Gulf Countries. GUtech, Oman with Nebel, S. GUtech, 2014.
- Conference organisation: Urban Oman – International Symposium on Urbanization in Oman with Bontenbal, M., & Nebel, S. GUtech, Oman 2013.
- Focal Point for the ETH Studio Basel Semester in Oman. German University of Technology in Oman, 2013.

- Intern mentoring programme, Royal Opera House internship programme, German University of Technology in Oman, 2013.
- Regional Coordinator: Autodesk Student Expert Group. German University of Technology in Oman, 2012.
- Campus relocation committee, German University of Technology in Oman, 2012.
- Faculty-Lead Student Design Competition: EcoHaus. German University of Technology in Oman, 2011.
- Coordinator development of fabrication lab, German University of Technology in Oman, 2011.
- Coordinator development of online learning platform "moodle", German University of Technology in Oman, 2010–14.
- Coordinator development of computer infrastructure increasing the number of fully licensed CAD workstations from 18 to 120, German University of Technology in Oman, 2010–11.

Conference Presentations and Lectures

- von Richthofen, A. (2018, July). Towards an Engagement Platform – Development of the Education Research Programme at FCL. Presentation, Future Cities Laboratory, ETH Singapore Center.
- von Richthofen, A., Cairns, S., & Jasper, A. (2017, December). FCL Lunch Talk – Urban Elements. Lecture, Future Cities Laboratory, ETH Singapore Center.
- von Richthofen, A. (2017, October). Urban Mining and Tropical Climate. Lecture, National University of Singapore.
- von Richthofen, A. (2017, October). Senses and Urban Spatial Reasoning and Representation. Lecture, Yale NUS, Singapore.
- von Richthofen, A. (2017, June). Urban Elements – Tools for Education Research at the Future Cities Laboratory, Singapore-ETH Centre. Lecture, ETSAB, Universitat Politècnica de Catalunya, Barcelona.
- von Richthofen, A. (2017, May). Education Research at the Future Cities Laboratory, Singapore-ETH Centre. Lecture, Tongji University, Shanghai.
- von Richthofen, A. (2017, March). Design, Co-Evolution and Participation in Urban Planning. Lecture, Urban Redevelopment Authority, Singapore.
- von Richthofen, A. (2017, January). Urban Spatial Reasoning and Representation. Lecture, Yale NUS, Singapore.
- von Richthofen, A., & Nebel, S. (2016, December). Urban Oman – Booklaunch and Exhibition Vernissage. Lecture presented at the Habitat Unit, TU Berlin.
- von Richthofen, A. (2016, December). Rural-Urban Transformation in Oman. Lecture presented at the IPS:

International Planning Sessions – Experts discuss Urban and Regional Challenges, TU Dortmund.
- von Richthofen, A. (2016, November). Circular Material Economies and Urban Mining. Lecture, National University of Singapore.
- von Richthofen, A. (2016, September). Report from the 2016 E4D Summer School with ETH Global at TU Delft. Lecture presented at the Annual Conference, Future Cities Laboratory, ETH Singapore Center.
- von Richthofen, A., Deffner, V., & Babar, Z. (2016, August). Arab Gulf Cities in Transition: Space, Politics and Society. Introduction Lecture presented at the Gulf Research Meeting, Cambridge.
- von Richthofen, A. (2016, April). Sand – an (in)finite Resource? Introduction Lecture presented at the ETH Global Engineering for Development (E4D) Summer School, TU Delft.
- von Richthofen, A. (2016, April). Visualising material stocks and flows in buildings of Singapore. Lecture, Future Cities Laboratory, ETH Singapore Center.
- von Richthofen, A., & Hanakata, N. (2016, February). Terrain, Topography and Territory – Concepts and representation of urban spaces. Lecture, Yale NUS, SIngapore.
- von Richthofen, A. (2015, December). Il metabolismo urbano. Invited Lecture presented at the Il progetto di riciclo, Facoltà di Architettura dell'Università degli Studi di Catania, Siracusa.
- von Richthofen, A. (2015, November). Urban Mining: From Alternative Construction Materials to Sustainable Neighborhoods. Invited Lecture presented at the Architecture, Science and Technology, Singapore University of Design and Technology.
- von Richthofen, A. (2015, November). Productive Spatial Systems in Oman: Case-Study Al Batinah. Conference presented at the Ruralism, Braunschweig.
- von Richthofen, A. (2015, October). Alternative Construction Materials for Future Cities. Habitat III preparation conference presented at the Future Cities Lab, Jakarta.
- von Richthofen, A. (2014, March). Modeling Sustainable Neighborhoods in Oman. Presented at the Challenges of Urbanization in Arab Gulf Countries, GUtech, Oman.
- von Richthofen, A. (2014). Sustainable Urbanization Models for Conflict Zones. Invited Lecture, Al Quds University of East Jerusalem.
- von Richthofen, A. (2013). Greening the desert? Sustainability and Urbanization in the Gulf. Keynote presented at the Future

Cities Conference, Dubai Cityscape, UAE.

- von Richthofen, A., & Nebel, S. (2013). Towards Sustainable Patterns of Urbanization in Oman. Progress Report, GUtech, Oman.
- von Richthofen, A. (2012). Ferdinand von Richthofen: a manual for the traveling researcher – towards a chorologic model of geography. International Conference Presentation presented at the Archeologia delle Vie della Seta – Percorsi, Immagini e cultura materiale, Università degli Studi di Napoli, "l'Orientale".
- von Richthofen, A. (2012). Integrated Tourism Projects and the Impact of Urbanization in Oman. International Conference Presentation presented at the Exeter Gulf Conference, Center for Gulf Studies – University of Exeter.
- von Richthofen, A. (2012). Muscat Capital Area – Urbanisation Patterns at the Gulf of Arabia. Invited Lecture, Institute for Sustainable Urbanism – TU Braunschweig.
- von Richthofen, A. (2012). Parametric Design Beyond Form. Invited Lecture presented at the Catalyst architecture lecture Series, Sultan Qabous University.
- von Richthofen, A. (2012). Parametrie – von der Formgenese zur Organisation räumlicher Zusammenhänge. Invited Lecture, Fachhochschule Trier.
- von Richthofen, A. (2012). Sustainable Urban Planning and Civic Participation – The Mutrah Master Planning and Redevelopment Project in Oman. International Conference Presentation presented at the AIA – Middle East Architectural Design Days, Jeddah.
- von Richthofen, A. (2012). The Urban Form as Ornament – Mass-culture and the Politics of the Continuous (Sub-)-Urbanization in Oman. International Conference Presentation presented at the The Gulf Research Meeting 2012, Cambridge.
- von Richthofen, A. (2012). Vom Daten-Ornament zur Daten-Struktur. International Conference Presentation presented at the Beyond Rendering – Tagung der Deutschen Gesellschaft für Geometrie und Grafik, TU Berlin.
- von Richthofen, A. (2011). aurelVR Practice – Parametric Projects 2001–2009. Invited Lecture presented at the Marvelous Mondays Lecture Series, GUtech, Oman.
- von Richthofen, A. (2011). Mechanisms of Urban Sprawl in Muscat Capital Area. International Conference Presentation presented at the The Gulf Research Meeting 2011, Cambridge.
- von Richthofen, A. (2011). Muscat Capital Area – From Royal Decrees to Urban Sprawl, Mechanisms of Urban Production in Oman. International Conference Presentation presented at the the Winter School Middle East, Kuwait City.

- von Richthofen, A. (2011). Parametric Drawing – a novel approach to representation. International Conference Presentation presented at the Crossing the line: Drawing in the middle east – intersections of transdisciplinary practice and understanding, American University in Dubai.
- von Richthofen, A. (2011). Space and Politics of Urbanization in Muscat Capital Area. International Conference Presentation presented at the Fourth International Symposium on Architectural Theory, Lebanese American University, Beirut.
- von Richthofen, A. (2011). Sustainability as Strategy for Urban Development. International Conference Presentation presented at the OITE Urban Oman Conference, Muscat.
- von Richthofen, A. (2011). Top-Down Urbanism in the Gulf Region – Focus on Oman. International Conference Presentation presented at the ArchTheo 2011 – DaKam – eastern mediterranean academic research Center, Mimar Sinan Fine Arts University, Istanbul.
- von Richthofen, A. (2010). Educating Urban Designers in the Context of Oman. Invited Lecture presented at the Institut für Städtebau und Landesplanung, RWTH aachen.
- von Richthofen, A. (2010). Rule-Based Design Approaches in Architecture. Invited Lecture, TU Berlin.
- von Richthofen, A., & Negron Oberon, L. (2010). Scripting, Fabrication and Iterative Production. Workshop presented at the DMY Design Festival, Berlin.
- von Richthofen, A. (2009). Schwarzpläne – Politics and Space of 20*th* century urban transformation read from figure ground plans in Berlin. Invited Lecture presented at the German Language Center, The Ohio State University.
- von Richthofen, A. (2008). Metabolism – Lost and Rediscovered in Translation. Invited Lecture presented at the Knowlton School of Architecture, The Ohio State University.
- von Richthofen, A. (2008). Metabo–Urbanism, Cities Without Planning. Invited Lecture presented at the Knowlton School of Architecture, The Ohio State University.
- von Richthofen, A. (2008). Models – Concepts and techniques in architectural design. Invited Lecture presented at the Knowlton School of Architecture, The Ohio State University.
- von Richthofen, A. (2007). Editor of / Architecture as: Membranes, Landscapes, Codes, Proto-Computations. Invited Lecture presented at the Knowlton School of Architecture, The Ohio State University.
- von Richthofen, A. (2007). Shape vs Form – or the recast of Gestalt and Content in Post-critical theory. Kuwait University of Petrol and Engineering.

LIST OF PUBLICATIONS BY AUREL VON RICHTHOFEN

Books and Edited Collections

- Cummings, V., von Richthofen, A. & Babar, Z. (forthcoming). *Arab Gulf Cities in Transition: Space, Politics and Society*. ETH Research Collection.
- von Richthofen, A., ed. (2018). *Urban Elements – Advanced Studies in Urban Design*. Singapore: Singapore ETH Centre. https://doi.org/10.3929/ethz-b-000270354.
- Nebel, S., & von Richthofen, A. (2016). *Urban Oman – Trends and Perspectives of Urbanisation in Muscat Capital Area* (Vol. 21). Berlin: LIT Verlag.
- von Richthofen, A., Baumeister, J., & Werminghausen, M. (Eds.). (2012). *UPAD Yearbook 2012*. Muscat: GUtech.

Refereed Journal Articles

- Heim, B., Joosten, M., Rupp, F., & von Richthofen, A. (2018). land allocation by lottery and tribal clan-formation in residential developments in Oman. *City, Territory and Architecture*. https://doi.org/10.1186/s40410-018-0084-6
- Heim, B., Joosten M., von Richthofen A., Rupp F. (2018). "On the Process and Economics of Land Settlement in Oman: Mathematical Modeling and Reasoning in Urban Planning and Design." *Homo Oeconomicus* 35 (1): 1–30. https://doi.org/10.1007/s41412-018-0066-7.
- von Richthofen, A., Knecht K., Miao Y., Reinhard K. (2018). "The 'Urban Elements' Method for Teaching Parametric Urban Design to Professionals." *Frontiers of Architectural Research* 7 (3). https://doi.org/10.1016/j.foar.2018.08.002.
- von Richthofen, A. (2018). Planning without maps – A critical reconstruction of modern settlement patterns in Al Bāṭinah based on military maps. *Journal of Oman Studies*, *19*.
- Cummings V., von Richthofen A. (2017). "Urban Sustainability as a Political Instrument in the Gulf Region Exemplified at Projects in Abu Dhabi." Edited by Tim Freytag, Byron Miller, and Samuel Mössner. *DIE ERDE – Journal of the Geographical Society of Berlin*, Cities and the politics of urban sustainability, 148 (4): 253–67. https://doi.org/10.12854/erde-148-53.
- von Richthofen, A. (2015). Desert Sprawl. Rapid urbanisation: the transformation of the desert in Oman. *Topos, the International Review of Landscape, Architecture and Urban Design*, *93*, 96–101. https://doi.org/http://dx.doi.org/10.3929/ethz-a-010637913

– von Richthofen, A., & Langer, S. (2015). Evaluating the urban development and determining "peak-space" of Muscat Capital Area. *Trialog – Journal for Planning and Building in the Third World*, *111*(Urbanisation in the Gulf Countries). https://doi.org/http://dx.doi.org/10.3929/ethz-a-010637970
– von Richthofen, A. (2014a). Oman – das Gegen-Dubai? *Baumeister*, (14), 82–89. https://doi.org/http://dx.doi.org/10.3929/ethz-a-010637947
– von Richthofen, A. (2014b). Vanishing Omani Landscapes. *Topos, the International Review of Landscape, Architecture and Urban Design*. Retrieved from http://www.toposmagazine.com/vanishing-omani-landscapes/
– von Richthofen, A. (2007). 3 Ms of Metabolism. *Pidgin – Princeton Architectural Press*, *3*, 146–163.
– von Richthofen, A., & Kocher, L. (2003). Landscape Urbanism – Interview with Alejandro Zaera Polo on the Yokohama Port Terminal. *Trans – Journal of the Department of Architecture at ETH*, *11* (Transscape – City and Landscape).
– von Richthofen, A. (2003). Machinic Landscaping Spluegen – An Experimental Landscape Design Project. *Trans – Journal of the Department of Architecture at ETH*, *11* (Transscape – City and Landscape).
– von Richthofen, A., & Reber, M. (2003). Urban Sprawl in Switzerland – Interview with Marcel Meili on the Research of ETH Studio Basel. *Trans – Journal of the Department of Architecture at ETH*, *10* (TransAktion – Art and Architecture).

Chapters in Books

– Cummings, Veronika, Aurel von Richthofen, and Zahra Babar. "Arab Gulf Cities in Transition: Towards New Spatialities." In *Arab Gulf Cities in Transition: Space, Politics and Society*, edited by Veronika Cummings, Aurel von Richthofen, and Zahra Babar. ETH Research Collection, Forthcoming.
– von Richthofen, A. "Digital Tools, Pipelines and Protocols." In *Future Cities Laboratory: Indicia 02*, edited by Stephen Cairns and Devisari Tunas. Singapore ETH Centre: Lars Muller Publishers, 2019.
– von Richthofen, A. "Transferring Research Knowledge into Urban Design Education." In *Future Cities Laboratory: Indicia 02*, edited by Stephen Cairns and Devisari Tunas. Singapore ETH Centre: Lars Muller Publishers, 2019.
– von Richthofen, A. and Fabien Clavier. "Looking Behind the Screen of Big Data." In *Future Cities Laboratory: Indicia 02*, edited by Stephen Cairns and Devisari Tunas. Singapore ETH Centre: Lars Muller Publishers, 2019.

– von Richthofen, A. and Alberto Costa. “Taxonometric Insights: Emerging Tool Clusters and Research Links.” In *Future Cities Laboratory: Indicia 02*, edited by Stephen Cairns and Devisari Tunas. Singapore ETH Centre: Lars Muller Publishers, 2019.
– von Richthofen, A., Philipp Urech, and Adrianne Joergenson Wilson. “Physical Tool Taxonomy.” In *Future Cities Laboratory: Indicia 02*, edited by Stephen Cairns and Devisari Tunas. Singapore ETH Centre: Lars Muller Publishers, 2019.
– von Richthofen, A., & Hanakata, N. (2017). Conversation on Designing Future Cities with Measures for a New Urban Agenda with Richard Hassell. In S. Cairns & D. Tunas (Eds.), *Future Cities Laboratory: Indicia 01* (pp. 82–85). Singapore ETH Centre: Lars Muller Publishers.
– von Richthofen, A. (2017). Ferdinand von Richthofen: a manual for the traveling researcher – towards a chorologic model of geography. In B. Genito & L. Caterina (Eds.), *Silk Road Archaeology*.
– Hebel, D., Aigner, N., Fleck, D., Heisel, F., Javadian, A., Lee, S., ... Wisniewska, M. H. (2017). Shifting Paradigms: From Excvation to Cultivation. In S. Cairns & D. Tunas (Eds.), *Future Cities Laboratory: Indicia 01* (pp. 191–199). Singapore ETH Centre: Lars Muller Publishers.
– von Richthofen, A. (2016a). Modelling low-rise high-density neighbourhoods in Oman. In *Urban Oman – Trends and Perspectives of Urbanisation in Muscat Capital Area* (Vol. 21, pp. 191–202). Berlin: LIT Verlag.
– von Richthofen, A. (2016b). No urban desert! Emergence and transformation of extended urban landscapes in Oman. In Vanessa Miriam Carlow & Institute for Sustainable Urbanism ISU, TU Braunschweig (Eds.), *Ruralism – The Future of Villages and Small Towns in an Urbanizing World* (p. 296). Berlin: Jovis.
– von Richthofen, A. (2016c). Parameters of urban expansion in Oman. In *Urban Oman – Trends and Perspectives of Urbanisation in Muscat Capital Area* (Vol. 21, pp. 109–126). Berlin: LIT Verlag.
– von Richthofen, A. (2016d). Patterns of urban growth and expansion: the Al Khoud case study. In *Urban Oman – Trends and Perspectives of Urbanisation in Muscat Capital Area* (Vol. 21, pp. 91–108). Berlin: LIT Verlag.
– Nebel, S., & von Richthofen, A. (2016a). Urban Oman – Editorial. In *Urban Oman – Trends and Perspectives of Urbanisation in Muscat Capital Area* (Vol. 21, pp. 15–20). Berlin: LIT Verlag.
– Nebel, S., & von Richthofen, A. (2016b). Urban sustainability

in the Omani context. In *Urban Oman – Trends and Perspectives of Urbanisation in Muscat Capital Area* (Vol. 21, pp. 249–258). Berlin: LIT Verlag.
- Nebel, S., & von Richthofen, A. (2016c). Urbanisation in Oman – Background and trends. In *Urban Oman – Trends and Perspectives of Urbanisation in Muscat Capital Area* (Vol. 21, pp. 25–36). Berlin: LIT Verlag
- von Richthofen, A. (2016e). Visualizing Urban Form as Mass Ornament in Muscat Capital Area. In N. Mounajjed (Ed.), *Visual Culture(s) in the Gulf: An Anthology* (pp. 137–158). Cambridge: Gulf Research Centre. Retrieved from http://dx.doi.org/10.3929/ethz-a-010637956
- Hebel, D., & von Richthofen, A. (2015a). Alternativen inklusive – von einem erweiterten Verständnis unserer Disziplin. In A. Gerber & S. Kurath (Eds.), *Städtebau, Stadtentwicklung, Raumplanung: Braucht es noch uns Architekten und Architektinnen?*
- von Richthofen, A. (2015). Oman's Urban Turn. In ETH Studio Basel (Ed.), *Muscat and Oman – engineered land, a territorial research*. ETH-Zürich. Retrieved from http://dx.doi.org/10.3929/ethz-a-010335395
- Hebel, D., & von Richthofen, A. (2015b). Sand, eine endliche Ressource. In *Wie Sand am Meer, Reihe Kunst und Wissenschaft, Katalog zur Ausstellung* (pp. 08–11). München: ERES Stiftung.
- von Richthofen, A. (2010). Regelbasiertes Entwerfen im Unterricht. In S. Hoffmann (Ed.), *open-source School – Neue Synergien zwischen Schule und Kiez in Gropiusstadt*. Berlin: Universitatsverlag der TU Berlin.

Conference Papers

- von Richthofen, A., Zeng, W., Burkhard, R., Asada, S., Mueller Arisona, S., Schubiger, S., & Heisel, F. (2017). Urban Mining: Visualizing the Availability of Construction Materials for Re-Use in Future Cities. In *BuiltViz2017 – Visualisation in Built and Rural Environments*. London South Bank University.
- von Richthofen, A. (2014). Modeling Sustainable Neighborhoods in Oman. Presented at the Challenges of Urbanization in Arab Gulf Countries, GUtech, Oman.
- von Richthofen, A. (2012). Ferdinand von Richthofen: a manual for the traveling researcher – towards a chorologic model of geography. *Archaeology of the Silk Road: Routes, Images and Material Culture*, 165–185. Retrieved from http://www.archeozone.it/ConferenzeUNIOR/ViedellaSeta.html#p=176

– von Richthofen, A. (2011a). Space and Politics of Urbanization in Muscat Capital Area. In *Politics and Space*. Lebanese American University, Beirut. Retrieved from http://www.lau.edu.lb/news-events/conferences/architecture-political/docs/vonrichthofen.pdf
– von Richthofen, A. (2011b). The Wave-Breaker – A Novel Approach to Computer Aided Design Representation. In *Crossing the Line*. American University Dubai.
– von Richthofen, A. (2011c). Top-Down Urbanism in the Gulf Region – Focus on Oman. In *Dakam – Proceedings of the ArchTheo 2012 Conference* (pp. 392–402). Sinan Mimar University, Istanbul: Dakam.

Reports

– von Richthofen, A., & Cairns, S. (2018). Transformative Research on Future Cities – Sharjah Learning Event. Singapore ETH Centre. Retrieved from 10.3929/ethz-b-000294296
– von Richthofen, A., & Tomarchio, L. (2018). Knowledge Map: Smart-Cultural City Singapore (Report). Singapore: Singapore ETH Centre & Goethe Institut Singapore. Retrieved from 10.3929/ethz-b-000280034
– Cairns, S., von Richthofen, A., & Andrew, S. (2018). Disruptive Technologies for Development (Report). Singapore: Singapore ETH Centre & The World Bank Singapore Hub. Retrieved from https://doi.org/10.3929/ethz-b-000273998
– von Richthofen, A. (2018). With/Out Water – Studio Report (Report). Singapore: National University of Singapore. Retrieved from https://doi.org/10.3929/ethz-b-000280046
– Hebel, D. E., & von Richthofen, A. (2015, January). Invention Disclosure: Alternative Sand Materials.
– Nebel, S., & von Richthofen, A. (2014). Towards Sustainable Urbanization Patterns in Oman (Final report No. CBS-ORG-09-001). Muscat: The Research Council Oman.
– von Richthofen, A., & Scholz, W. (2013). Oman National Spatial Strategy (ONSS) with focus on urbanisation. Muscat: Supreme Committee of Planning.
– von Richthofen, A., Gronning, O., Baumeister, J., Gaube, H., Aziz, H., & Bontenbal, M. (2010). Consultant to Norplan Oman for the Mutrah Re-Development and Master-Planning.

Media Coverage

– Kirk, M. (2018, October 1). Can Oman Build a Better Planned City? *The Atlantic – Citylab*. Retrieved from https://www.citylab.com/design/2018/01/the-surprisingly-rational-persian-gulf-planned-city/550106/

– von Richthofen, A. (2016 5). The story of cities: the tales we missed. Retrieved from http://www.theguardian.com/cities/2016/may/27/the-story-of-cities-the-tales-we-missed?CMP=share_btn_tw
– Kirk, M. (2016). Experimenting with Public Transportation in Muscat. *The Atlantic – Citylab*. Retrieved from http://www.citylab.com
– Matheis, K. (2015, April 9). Smart nach Plan: Forschung am Future Cities Lab in Singapur. *WirtschaftsWoche Global*, pp. 44–49.
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– Gutech to hold symposium on urbanization in Oman. (2013). *Times of Oman*. Retrieved from http://www.citylab.com/cityfixer/2016/05/experimenting-with-public-transportation-in-muscat/481938/
– Kriegsheim, F. (2013). Sustainable Neighborhood in Oman. *Scitech TV*. Muscat. Retrieved from https://vimeo.com/55787927
– Report on Gutech EcoHaus Competition. (2012).*Y – Magazine*.

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– Nebel, S., & von Richthofen, A. (2012). UrbanOman.org. Retrieved March 30, 2015, from http://urbanoman.org/ ●